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DESIGN AND IMPLEMENTATION OF AN AUTONOMOUS SURFACE VESSEL

by

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13. ABSTRACT Autonomous vehicles are only beginning to make the impact that they soon will have in a variety of applications. Research is ongoing to provide unmanned vehicles with higher cognitive abilities in order to simplify or eliminate the role of an operator. Advancing the understanding and development of Autonomous Surface Vessels (ASVs), the objective of this research project, will be beneficial to not only the military, but also in many commercial and research applications. Multiple criteria were considered in selecting the type of vessel and maneuvering hardware most appropriate for the desired applications. A semi-planing monohull with an electric motor and single rudder was selected as the test bed for this research. In addition, sensors were chosen to provide the necessary data for an autonomous controller. These sensors were integrated onto a single circuit board which included a dedicated microprocessor for their operation and control. Different communication techniques were investigated to allow the primary microprocessor to pass information to a secondary microprocessor which produced the output for the control motors. Techniques for mathematically modeling the vessel were investigated, and physical experiments were conducted to determine the maneuvering parameters of the vessel, required for the model's development. From this model, a control system was developed to guide the vessel to a desired position following waypoints based on the input of the sensors. These waypoints were automatically determined from information stored on an off-board computer. Data was collected in order to improve the functionality of the sensors and navigational techniques. During this research, numerous challenges specific to small, low-cost ASVs were encountered and investigated. In the end, a fully functional low-speed miniature ASV was developed and tested in the waters surrounding the U.S. Naval Academy. This platform represents an important step forward in autonomous marine surface vessels.
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Abstract

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Multiple criteria were considered in selecting the type of vessel and maneuvering hardware most appropriate for the desired applications. A semi-planing monohull with an electric motor and single rudder was selected as the test bed for this research.

In addition, sensors were chosen to provide the necessary data for an autonomous controller. These sensors were integrated onto a single circuit board which included a dedicated microprocessor for their operation and control. Different communication techniques were investigated to allow the primary microprocessor to pass information to a secondary microprocessor which produced the output for the control motors.

Techniques for mathematically modeling the vessel were investigated, and physical experiments were conducted to determine the maneuvering parameters of the vessel, required for the model's development. From this model, a control system was developed to guide the vessel to a desired position following waypoints based on the input of the sensors. These waypoints were automatically determined from information stored on an off-board computer. Data was collected in order to improve the functionality of the sensors and navigational techniques.

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1. Background

Today's armed forces, as well as the civilian world, are experiencing significant advances in the areas of unmanned and autonomous vehicles. However, these advances have not been all-inclusive. Land, air and undersea vehicles have received the majority of the attention, leaving much room for the development of unmanned, autonomous surface vessels (ASVs). These vessels would be very useful in today's maritime environment. Applications for harbor control and security, covert surveillance, and interdiction are logical conclusions of such research. Using automated craft in harbor applications would reduce the cost and required manpower, or allow personnel to focus on other tasks to increase efficiency. A small ASV would be more difficult to detect than a full-sized vessel designed to carry personnel, so it would be a useful tool in reconnaissance. With high-speed capabilities, an ASV would be able to track and send information regarding unknown or hostile contacts to a control station that could then identify and prosecute the possible threat. Significantly, Admiral Vern Clark, USN, the former Chief of Naval Operations, when communicating his plan for future readiness, instructed his leaders to "survey and report on unmanned platforms that exist in other services or branches of the US government, or that are in near-term development (able to be deployed in experiments), and that provide potential capabilities to improve counter-terrorism and AT/FP (anti-terrorism/force protection) effectiveness." [1] Additionally, the Naval Transformation Roadmap for 2003 called for "situational awareness in restricted waters, harbors and anchorages" as well as "the ability to detect, identify, and neutralize personnel, cargo and vehicular threats to moored naval vessels [2]. This platform could serve in any of these capacities, as well as many more.

While ASVs have a clear mission in the modern environment, it is not obvious that the ASV is the best solution for such missions. Unmanned underwater vehicles (UUVs) and

unmanned aerial vehicles (UAVs) have been successfully deployed for missions similar to those discussed above, which can lead to doubt as to the real value of yet another type of vehicle. The main advantage of ASVs over UUVs is that ASVs can achieve much greater speeds with lower power requirements and do not generally encounter the same level of environmental resistance. ASVs have the advantage over UAVs in station-keeping, on-station time and robustness. An engine failure or catastrophic environmental disturbance will frequently result in a downed UAV, while an ASV may remain on-station and functioning after being swamped, losing power to an actuator, or numerous other malfunctions.

Although there are many foreseeable applications for an ASV, there has only recently been significant attention in this area. This presents a unique opportunity for this project to present some new and valuable research. While there are no definite explanations as to why surface vessels have taken so long to gain attention, there are some logical possibilities to consider. Primary among these is that, until recently, there has not been a great recognized need for ASVs. It is easy to imagine the practical advantages of land and aerial vehicles on the battlefield, but the unmanned surface vehicle seems to have a better role as a homeland defense platform, which has only gained attention in recent years. Another possible reason surface vessels have not been automated is the lack of crossover between robotics and surface technology when compared with aerial systems. Aviation has long relied on fly-by-wire techniques, which means the pilot's inputs are analyzed by a computer which controls the flight surfaces accordingly. This interaction significantly aided the development of UAVs. Surface vessels, however, are more frequently mechanically controlled, as there is generally no need for the rapid and difficult maneuvering procedures required by aircraft. A third factor that could have prevented research into surface vessels is the dynamic nature of the terrain. In general, land

is solid, which simplifies the control algorithms required for maneuvering. The air and underwater environments are dynamic, but not nearly to the extent of a littoral surface zone where waves and moving obstacles create a fluctuating terrain that is difficult to model and predict.

However, the Navy has realized the potential benefits of an unmanned surface vessel (USV), and produced one which completed its first operational testing on 13 December 2003. Designated the Spartan Scout, this platform is a major step in the direction of ASVs. The program was launched in 2001 at the Naval Undersea Warfare Center (NUWC) in Newport, R.I. after President Bush made an initial call for increased research in unmanned vessels [3]. The Spartan has been described as "an unmanned surface vehicle designed for an array of high-risk missions including intelligence, surveillance, reconnaissance, and mine warfare in the littorals." [4] In essence, it is a rigid hull inflatable boat (RHIB) that has been outfitted with engine and control modifications, which enable it to be operated remotely through a standard computer keyboard and mouse interface, as well as the capability to support a variety of sensors and weapons [3]. The initial demonstrations were well received and Admiral Clark called for an acceleration of the development program in order to get the Spartan into the fleet [4]. However, it is a large platform. It requires manpower to deploy and retrieve, and it has an unnecessarily large radar signature and consequent high detectability. Additionally, it is only semi-autonomous; three operators are required to run the Spartan. The Spartan does at least demonstrate the Navy's support for research and development of USVs.

2. Problem Statement

Based on the observations made regarding ASVs, this Trident Scholar project focused on the development of a small, capable ASV. The primary objective was to develop an ASV that could travel on the water from a given initial location to a desired final position. This system includes a hull, propulsion, and basic non-autonomous maneuvering controls that have already been designed and tested in other applications, specifically radio controlled boating. In addition, various sensors were incorporated into the control of this boat to allow it to complete the course autonomously.

The sensors on the developed ASV allow the system to accurately and safely navigate while traveling at low speed. This required the development of a low-speed control system, relying on techniques from classical control and dynamic modeling of ships [5]. The dynamics of a hull traveling over water on plane are much more complex and there is no known system that can control it as accurately as a hull acting in displacement mode can be controlled. Factors such as skipping over waves and consequently landing back on or even in the water (including "porpoising" and "slamming" effects) make such control difficult. Therefore, the sensors on board the vessel were designed with the capabilities of serving as feedback sensors for a high speed control system. Data received from these sensors can be useful for refining the low speed controller for use under different conditions. The objective of this research was for the vessel to guide itself to the desired destination, at low speed if necessary. The data collection process was also important, but data collection has more significant implications for future tuning of the controller than as an actual objective of this research.

3. Platform

In order to develop an autonomous surface vessel (ASV), it was necessary to begin with an appropriate platform to automate. There were a few important characteristics that such a platform had to demonstrate in order to be considered as a proper test bed. An appropriate hull had to be selected, as well as a suitable power source and propulsion system. These components make up the basic platform that was converted from a remotely controlled system to an autonomous one.

3.1. Hull

The logical starting point for this selection process was to determine the hullform that would be used for this research. The type and size of the hull were the parameters that were considered. The size was driven largely by logistical factors, but specific applications were also considered. It was necessary for a single person to be able to transport the vessel to different testing environments throughout the course of the research, so the maximum size of the hull was necessarily limited. Deployment of the vessel could not require significant equipment, so a small vessel was desirable. Additionally, certain applications of an ASV are ideally suited for a small vessel. Scouting and reconnaissance missions, for example, can be much more successful if the size of the observer makes it difficult to detect. A small vessel could also be useful as a peripheral sensor deployed by a larger unmanned vessel operating in coordination. A group of such vessels could cover a large area over a short time, increasing the base vessel's capabilities. There was a limit to the minimum size of the vessel, though, because the hull had to be large enough to safely operate in the Severn River while loaded down with the sensors and additional batteries necessary for autonomous control. There had to be enough space both above and below

deck to facilitate the placement of these sensors in such a way as to prevent interference either with each other or with the other hardware associated with the platform.

The second consideration during the hull selection process was the type of hull to select. There were a variety of options available, ranging from highly refined racing hulls to intricate scale models of ships. Many of the more exotic designs were disregarded based on their limited capacity or deck space, which left two primary candidates. Multihull vessels, such as catamarans, provided a great deal of stability as well as ample deck space for the environmental sensors. However, dry space under the deck for microprocessors and other sensors was somewhat limited. A mono-hull design also exhibits stability and provides enough deck space for sensors, but there is generally more space below deck than a catamaran of similar dimensions. Also, the hydrodynamics of a mono-hull are understood and documented better than those of a catamaran [5]. Since determining the properties of a catamaran or other multihull vessels would be a time-consuming process, and was not an objective in this project, the better understanding of the monohull was desirable. It was also desirable to have a hull capable of traveling on plane. When a vessel is "on plane," it is supported primarily by dynamic interaction with the water, as opposed to the buoyancy forces common to "displacement mode." Having a vessel capable of planing allows for extension of the low-speed controller to more challenging operational domains, and also permits *in situ* study of planing dynamics.

As a result of these decisions, a search was conducted for a monohull that was capable of traveling on plane and carrying a significant amount of extra equipment. The PIP Triton Mono, designed by Toysport [6], was determined to be an appropriate hull for this research (Figure 1). It is 0.805 m (32 in) long and 0.245 m (9.5 in) wide, so it is easy to transport, launch, and recover. It is 0.10 m deep at the deepest point, which provides ample space for the sensors and

processors that need to be mounted below deck. Above deck, there is more than enough space for the ranging apparatus. The system, including the components necessary for propulsion and maneuvering, weighs 3.08 kg (6.80 lb). Static tests and simple initial trial runs indicated that the vessel would be able to maneuver with an additional 1.0 kg (2.2 lb) of hardware. These tests set the design point and drove the component selection process to guarantee the additional sensors would not weigh more than was allowable.

Figure 1: PIP Triton Mono

3.2. Propulsion System

During this selection process, it was also necessary to consider the equipment that would propel the vessel. These considerations were made concurrent to the hull selection because most hulls are designed for a specific propulsion type. The major decision for this selection process was between electric and fuel powered components. The Triton hull was designed for electric propulsion, but both systems were considered before the hull was ultimately chosen. Fuel systems boasted more power and endurance than most electric systems of comparable weight. However, fuel systems also presented a few significant disadvantages. From a logistical perspective, frequent handling and requisition of fuel seemed to be a hazardous and time-

consuming process. Batteries, on the other hand, can be recharged as necessary and are relatively safe to handle. Additionally, it would be easier to work with a completely electric system than to have electronic sensors and a fuel powered engine. Some fuel engines can have difficulty starting under certain conditions, whereas electric motors tend to be more reliable. Finally, although they are expensive, some batteries are able to produce enough power for the vessel to be functional. These factors led to the decision to pursue an electric propulsion system.

Once that decision was made, the process of selecting a motor began. In order to enable future research on planing dynamics, it was necessary to select a motor capable of high speeds. In radio controlled boating fields, brushless motors are more popular than traditional motors because they weigh less and are more reliable. They also cause less electromagnetic noise to affect sensors and they are able to run at higher speeds. Typically, the brushes are the first part to wear out, so eliminating this part will increase the longevity of the motor. The brushless motor that was best suited to the Triton hull was the Nemesis Blue 540 9XL. This motor is capable of producing 1853 rpm/V [7]. Over the course of the testing, this motor proved more than capable of handling the added load of the sensors and functioned through some significant environmental disturbances.

Figure 2: Nemesis Blue

This motor is powered by a pair of 8.4V lithium-polymer cells (Figure 3). These cells are rated at 7500 mah, with a discharge rate between 10 and 12 C. This means that they are able to provide over 75 A of current for short periods of time. At a more sustainable rate, they are capable of producing 12 A for 3 hours [8]. They were chosen because of their improved performance over traditional alkaline cells. While they have less weight and volume, they are capable of producing more current for a longer period of time. This particular advantage was important for this design process because weight was going to be a constraint, but the vessel also needed the capability of running for at least an hour without recharging. Also, lithium-polymer batteries have a relatively flat discharge curve, so they provide almost constant voltage throughout the discharge cycle (Figure 4). Lithium-sulfur batteries also exist, but their expense and long lead time in procurement put them out of the scope of this project. The lithium-polymer cells seemed an appropriate blend of functional and economical considerations. As different tests were conducted, the batteries repeatedly demonstrated their capability of powering the motor throughout the testing procedure. They performed well through some functional tests that lasted almost three hours.

Figure 3: Lithium-Polymer Batteries

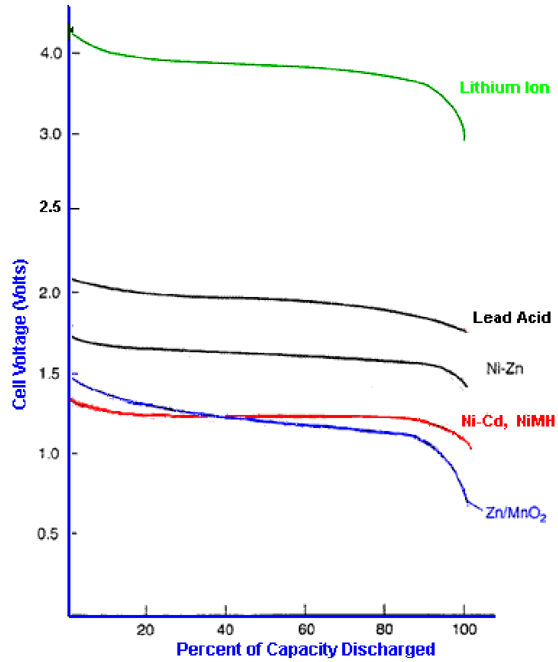

Figure 4: Discharge rates for different battery types [9]

The remainder of the propulsion system was compiled of standard remote controlled boating parts. The vessel's heading is controlled by a single rudder. Other direction control methods were considered, such as a directional propeller or multiple propellers with differential drive, but the simplicity and robustness of the fixed propeller and single rudder was appealing. The motor commands are processed by a speed controller. This device serves to convert the R/C servomotor commands to pulse-width modulated signals which are needed for the DC motor. The R/C signal can be directly interpreted by the servomotor used to operate the rudder because that signal is coded specifically for that type of motor. A DC motor requires a translation of the regular R/C signal in order to function properly.

These components were installed in the Triton hull in order to create the platform that served as the test bed for autonomous vehicle design. With these components, the vessel was able to operate in remote control mode, which was useful for identifying general maneuvering

properties of the vessel. It was tested to ensure functionality and demonstrated the ability to travel in displacement mode as well as planing mode. In planing mode, the vessel is greatly affected by even relatively small waves. At lower speeds, the vessel is able to handle significantly greater sea states. In the end, a capable platform was ready to begin the transition from remotely controlled to autonomously controlled operation.

3.3. Platform Selection Conclusions

At this point, the physical system that served as the test bed for this autonomous design was developed. The necessary hardware was in place such that the vessel was capable of maneuvering at both high and low speeds with a remote control. There were many steps to be taken between this point and autonomous control, but the investigation and procurement of a functional platform was a critical foundational step in this research process.

4. Sensors

Once the platform was designed, the focus shifted toward the development of an integrated sensor board. This sensor board was designed for two distinct missions for ASVs:

1) To provide measurements so that the autonomous controller would have the information necessary to safely guide the vessel in displacement mode at moderate or low speeds.
2) To provide foundational capabilities for more advanced modeling and *in situ* testing in future research efforts, potentially at higher speeds and under more significant maneuvering requirements.

To support the first mission, the controller needed to know its position on a global scale. In addition, it had to know its orientation and the deviation from its original global position. Information about heading was important, as well as the ability to locate and measure its distance to potential obstacles. To support the second mission, it was necessary to develop sensors that could provide a wide variety of additional information regarding the vessel's dynamic motion.

Based on these design criteria, an integrated sensor module was developed that incorporated a GPS receiver, a magnetic compass, rate gyros, and an accelerometer. Additional communication channels with the integrated Rabbit 3000 microprocessor were available for peripheral sensors, such as ranging devices. The NavBoard (Figure 5) served as the core of the navigation system for the ASV.

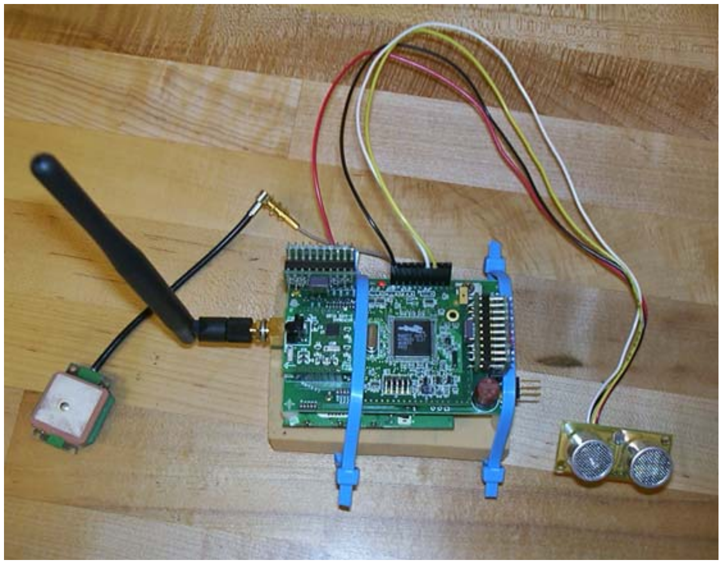

Figure 5: NavBoard

4.1. GPS

The natural first choice for a modern navigational sensor was the GPS receiver. This sensor provides the user with information about its position on the earth. A GPS receiver also provides information about direction, speed over ground, and elevation, if enough satellites are visible. This information is invaluable in any navigational application. An important contribution from this sensor is the ability to determine the initial position of the vessel. It is this information that will allow the path planning process to begin, which must occur before any subsequent travel is achieved.

A Lassen SQ GPS receiver was chosen for this research. This receiver updates at one-second intervals. It is rated to be accurate within 6m 50% of the time [10]. These specifications demonstrate some of the major limitations of GPS receivers. While they provide useful information that is difficult to determine otherwise, that information is frequently not completely accurate, with errors that can be on the order of several vessel lengths. The slow update rate

means that, at high speeds, significant position changes could occur between samples that could be hazardous to the vessel. Also, since GPS receivers operate based on communication with satellites, it would be possible to jam that signal. If the GPS receiver was the only source of position information, this would not be a useful situation. Therefore, it was necessary to include alternative means of achieving position data. A process known as Kalman filtering can be used to combine information from a GPS receiver with that from other sensors to create a highly accurate position solution [11].

4.1.1. Background

Since a GPS receiver was going to be an integral part of the navigation process, it was necessary to understand the functionality of that system. A GPS receiver works because it is able to receive temporal data from a group of satellites and mathematically convert that information into a location. The Lassen SQ GPS receiver is designed to be able to provide the user with additional information that drastically increases the number of tools available for navigation. The module has the capability of outputting different sentences which contain a preset group of information [12]. This information is generally some combination of latitude and longitude, speed, course, time, and satellite picture. One of the sentences, referenced as the GGA message, contains information about the GPS fix. In addition to latitude and longitude, it provides a quality indicator which determines if there is a fix at all, if it is a standard GPS fix, or if it is a more accurate DGPS fix. It also contains information about the number of satellites in use, the altitude of the antenna, and the time since the last DGPS update [12]. Each of the seven different sentences provides a different group of information which would all be useful in certain applications. For this research, the Recommended Minimum Specific GPS/Transit Data (RMC) sentence was used. This sentence provides latitude, longitude, the speed over ground in knots,

the track made good in degrees true, and other information that was not used in this application. This information was the basis for the navigational strategy for the vessel.

4.1.2. Initial Results

Initial research with the GPS receiver was not encouraging. The first tests were conducted using the GGA message, since there was some interest in the quality of the GPS fix and the number of satellites that were providing that fix. These tests showed that the fixes provided by the receiver ranged widely over time. The GPS receiver was placed in a single position, and the results from that measurement ranged 71 ft north and south and 29 ft east and west (Figure 6). For a small vessel, these deviations would be significant, and result in unsatisfactory performance of the navigation system. A second problem with the original design was that the software that had been written to operate the GPS receiver was flawed. An error would occur after approximately five minutes of reading data that would ultimately cause the microprocessor to stop functioning. This error had to be addressed because it would not be possible for the vessel to operate autonomously if the main microprocessor shut down so frequently. As a result of these observations, significant efforts were made to improve the quality of the GPS data reception system.

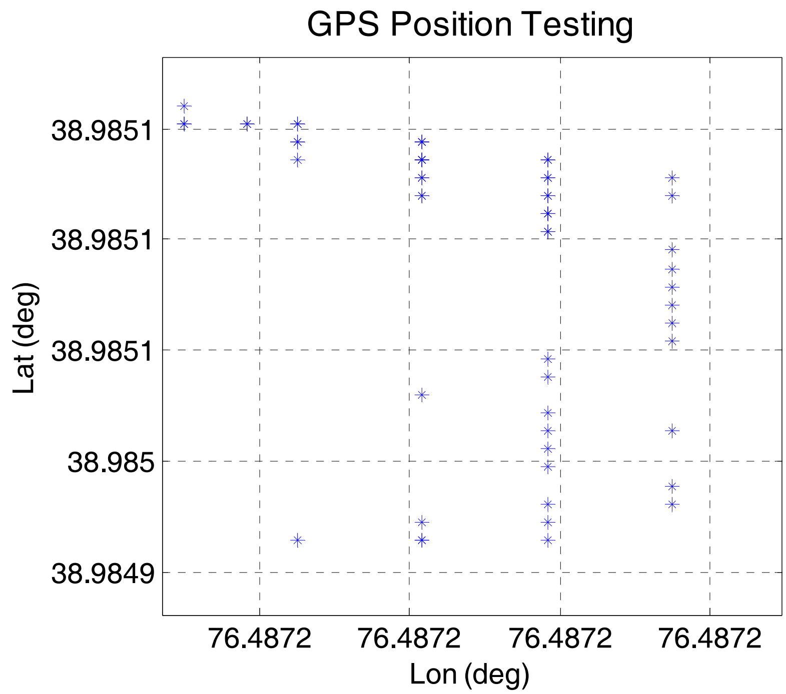

Figure 6: Original GPS data (0.0002° longitude per division)

4.1.3. New Module

While these efforts were ongoing, it became necessary to exchange the original NavBoard with one that had been slightly redesigned in an attempt to increase the accuracy of the magnetometer. The GPS receiver on this NavBoard had never been initialized, so there was a great deal of work to be done before it would receive useful GPS data. Each NavBoard is equipped with a backup battery that serves the GPS receiver. This is because the GPS receiver, once it is first successfully initialized, stores an almanac of satellite positions into memory so that it can quickly locate satellites on each future initialization. This first time the receiver is enabled, it can take up to twenty-five minutes to locate enough satellites to produce an accurate fix, but once this is accomplished it can produce a fix in less than a minute.

However, experimentation with the new NavBoard showed that the GPS receiver was not able to properly initialize. The initial attempts were simple, involving activating the NavBoard

and monitoring the output of the GPS receiver. After multiple days of testing for at least forty minutes during each attempt, a new strategy was devised. A separate GPS receiver and output display was used to ensure that there were satellites in view and that a GPS fix was available. With that information, it was possible to isolate the problem to either the hardware or software on the NavBoard, instead of the weather, nearby buildings, or other possible obstructions to GPS signals.

At this point, however, a separate problem was encountered. The data sentence output by the GPS receiver was designed to have a specific format so it could be properly read and deciphered by the Rabbit. Even if there were no data present, the sentence was still designed to have a recognizable form. Instead of following this pattern, though, the GPS receiver began to output a series of seemingly random characters, sometimes including some hexadecimal values but more frequently unrecognizable. This separate malfunction greatly increased the complexity of the problem because now it was more difficult to test the hardware involved with the system since the software did not work. For this reason, the focus shifted from attempting to initialize the GPS receiver to being able to consistently output the correct sentence structure.

The ultimate solution came as a result of a deeper understanding of the operating procedures of the NavBoard. The GPS receiver is preset to initialize under specific communication standards defined as TSIP mode. In this mode, the GPS receiver communicates using a 9600 baud rate. This mode receives and outputs GPS data, but that data are not in a readily usable form. For this reason, it was desirable to change the receiver from TSIP mode to NMEA mode, which outputs the GPS data in a more common form. However, NMEA standards dictate a baud rate of 4800. In order to facilitate this conversion, the serial port which communicates with the GPS receiver must be opened at 9600 baud so the commands can be sent

to change from TSIP to NMEA mode. At this point, the serial port must be reopened at 4800 baud so the new data can be received. This process was included in the initialization code, and all the necessary commands were given at each baud rate so the output should have been correct. However, the serial port was being reopened at 4800 baud immediately after the previous communications had been completed. The speed at which this baud conversion process took place was such that it was possible for some data to become corrupt in the conversion process. This was the source of the unrecognizable data sentences that the GPS receiver was producing. Adding a short delay between the two communication phases successfully rectified the process so that the GPS receiver was able to initialize properly.

Since the proper data sentence was now being read from the GPS receiver, it was possible to return to testing the hardware to determine why the receiver was not able to produce valid data. The second GPS unit proved to be critical in this phase of research. Since it was clear that this unit was functional, it seemed reasonable to swap single pieces of hardware between the two sensor boards in order to isolate the source of the problem. There were three main points where a failure could occur that would cause the sensor not to work. A bad connection between the sensor and the microprocessor would definitely create problems, but since the Rabbit was now able to read properly formatted sentences, this did not seem likely. This meant that either the GPS receiver itself was not functional or the antenna did not work. The first test was to swap GPS receivers and see which would receive data first. The GPS receiver from the NavBoard, which had never displayed valid data, was able to output GPS coordinates in less than five minutes when it was mounted on the separate testing board. The previously functioning receiver that had been switched to the NavBoard never received data. Since the receiver itself seemed to be functional, this indicated that the source of the problem was the antenna. When the original

GPS receiver was returned to the NavBoard and the antenna from the testing board was attached, it quickly displayed valid GPS data. Conversely, the testing board was unable to output any data with the antenna from the NavBoard attached. This confirmed that the antenna that had been attached to the NavBoard did not work properly. It was replaced and the GPS receiver quickly produced valid data. As a result of this testing procedure, two separate problems were identified and solved. Although the solutions to both of these problems were relatively simple in their execution, discerning the actual source of the faults in order to develop a solution proved to be a difficult, time intensive process.

4.1.4. Current Performance

With a new antenna attached to the GPS receiver which was properly initialized, tests of the data quality were conducted. The new receiver was able to locate satellites and produce data faster than the receiver on the original NavBoard. The fixes were also more consistent over time, indicating a more reliable sensor. Figure 7 shows the results using the new receiver at a high resolution. During the entire testing process, during which sixty-nine measurements were taken, only two values of position were returned. These values were 6 ft apart vertically and aligned horizontally. This information lent validity to the other pieces of the RMC sentence that were of interest in this research, namely the course and speed information. With a positive location fix, as well as speed and course information, it was possible to begin to design a control algorithm to actually accomplish autonomous navigation.

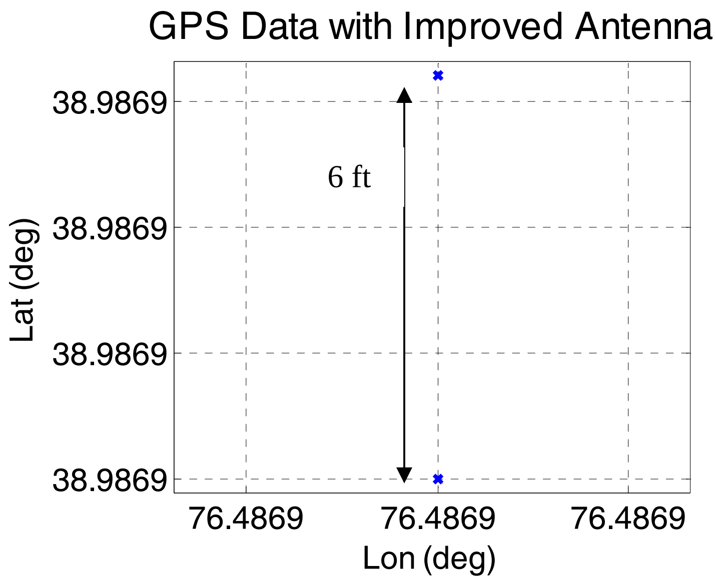

Figure 7: Improved GPS data

4.2. Magnetometer

Magnetic compasses have been helping navigators find their way for many years. The ability to accurately and reliably determine the direction of travel and the direction to reference points is fundamental in many navigational strategies. The MicroMag3 serves this purpose on the NavBoard. With an update rate of 2000 times per second [13], it provides information that is much closer to real-time than the GPS receiver. Also, this sensor can provide heading information even while the vessel is motionless, whereas the GPS receiver depends on position changes to provide this information. Initial tests with the magnetometer demonstrated basic functionality, meaning that the compass successfully output values between 0° and 360°. Exact calibration of the compass was not initially accomplished because these initial tests were conducted indoors around computers, desks, and other equipment that could provide significant interference to the magnetic field affecting the sensor. The remainder of the tests were conducted outside in order to limit interference.

The magnetic field of the earth is three-dimensional, and this sensor has the capacity to measure that field in all three dimensions. This means that a specific calculation process was necessary to determine the actual heading based on the readings on each of the three axes. Since this measurement process was fairly complex, it was significant that the sensor was able to produce the appropriate values during this initial testing phase.

Exact calibration testing took place at a later time and produced significant results. It was noticed that the output of the magnetometer did not change at a constant rate as the sensor was rotated. For a 360° rotation, the output of the sensor successfully started and stopped at the same value, but there were discrepancies in between. Casual observations showed that when the sensor had been rotated about 270°, the output was only around 180°. Then, during the last 90° of rotation, the measurement changed another 180° so that it ended at the same value as it started. For this reason, it was necessary to spend some additional time investigating the performance of this particular sensor. A few important conclusions were developed.

The first significant performance characteristic that was noticed as a result of this experimentation process was a drastic difference between the output of the compass when the wireless modem was transmitting and when it was removed from the NavBoard (Figure 8). The output from the magnetometer deviated in both conditions, but the direction of the deviation was completely opposite. This observation was significant because it was indicative of a likely source of the poor performance of the magnetometer. Not only could large metal objects in the vicinity of the sensor degrade the accuracy of the output, but some of the small pieces of electrically active hardware mounted on the NavBoard, in the immediate vicinity of the magnetometer, appeared to have detrimental effects as well.

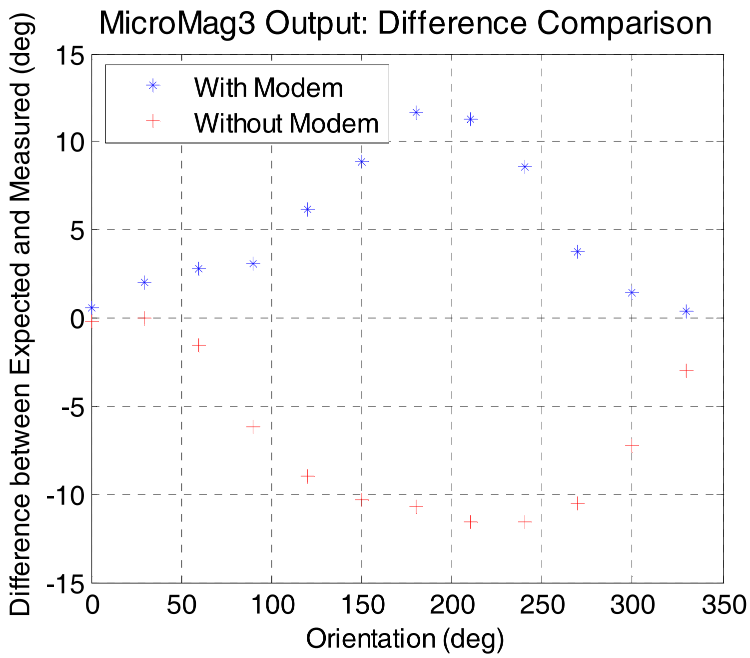

Figure 8: Magnetometer output comparing the influence of the wireless modem

As a result of this realization, some minor modifications were made to the NavBoard in an attempt to improve performance. The original version had the rate gyros mounted in such a way that they were farther off the board than they needed to be. They were higher than the magnetometer, so some of the spacing was removed so that they were mounted closer to the board, which made them more out of the way of the magnetometer. This new NavBoard version improved performance slightly, but even without the wireless modem mounted on the NavBoard, the signal still exhibited significant but consistent and smooth deviations throughout the measurement spectrum (Figure 9).

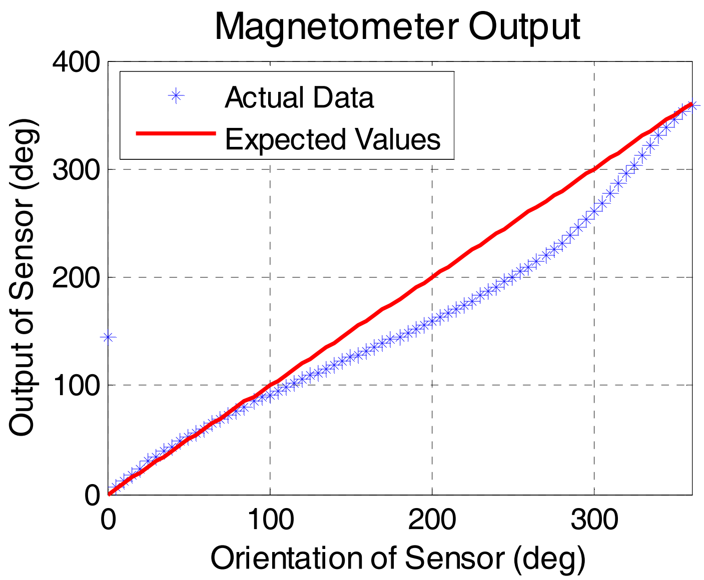

Figure 9: Magnetometer output with deviation from expected results

Although this performance flaw prevented the magnetometer from measuring absolute headings, the measurements it was taking were useful in the control algorithm. The measurement from the sensor would remain constant for a specific heading, so this value was used as a backup course in case the GPS signal was lost. Further efforts with signal processing would result in a more reliable output, and this level of performance was effective in giving the vessel the necessary sensor feedback in order to achieve autonomous navigation.

Table 1: Standard vessel terminology

DOF		Forces and moments	Linear and angular velocities	Position and Euler angles
1	Motions in the *x*-direction (surge)	X	u	X
2	Motions in the *y*-direction (sway)	Y	v	Y
3	Motions in the *z*-direction (heave)	Z	w	Z
4	Rotation about the *x*-axis (roll, heel)	K	p	Φ
5	Rotation about the *y*-axis (pitch, trim)	M	q	θ
6	Rotation about the *z*-axis (yaw)	N	r	ψ

4.3. Rate Gyros

The magnetic compass complements the GPS receiver by providing a timely direction signal, but it does not directly help determine position. Indirectly, however, it can be extremely beneficial. The derivative of the direction signal is the directional rate of change, or the yaw rate (Table 1). This rate information is similar to the data that is received from the two rate gyros on the NavBoard. These sensors are designed to measure the rate of rotation about the axis on which the sensor is oriented. On the NavBoard, the compass measures rotation about the z-axis, while rate gyros measure the rotation about the x- and y-axes. This means that they are designed to provide the pitch and roll information. The particular sensors that were used on the NavBoard are the ADXRS150 rate gyros. They are sensitive up to 12.5 mV/°/s [14].

Although the rate of rotation about the different axes is nominally useful, their real contribution is the ability to determine the vessel's orientation relative to an earth-fixed reference

frame. This is a problem common to autonomous vehicles and robotics in general, under which it is necessary to mathematically define the relative position and pose of a moving body with respect to some inertial reference frame. The most common set of coordinates used for autonomous vehicles is shown in Figure 10, where the vessel possesses a local coordinate frame $\{X_v, Y_v, Z_v\}$ corresponding to the surge, sway and heave directions (Table 1) and the world coordinate frame $\{X_w, Y_w, Z_w\}$ follows the standard North, East, Down convention. The world coordinate frame is anchored in the inertial coordinates at a convenient spot (such as the initial vessel point) and the vehicle coordinate frame moves with the vessel. Using tools from robotics [15], it is possible to denote the vessel's configuration (position and orientation, or pose) using a *transformation matrix*, the details of which are not necessary for this discussion. The rate gyros are useful in determining the orientation of the vessel in the inertial coordinates.

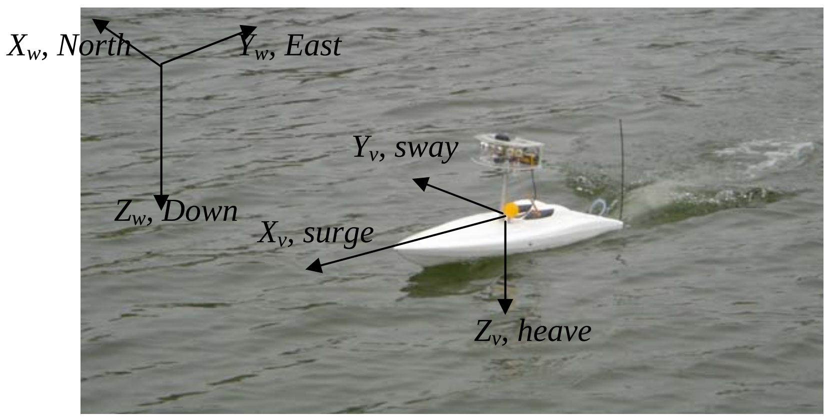

Figure 10: Coordinate frames for an autonomous surface vessel

If the initial orientation of the vessel is known in the inertial frame, the gyro rate information can be integrated to determine the new orientation. For small sample periods, this integration can be accurately approximated as:

$$\theta_k = \theta_{k-1} + \frac{\Delta t}{2}\left(\omega_k + \omega_{k-1}\right) \tag{1}$$

where θ is the angle between the vessel's axis and the world coordinate frame axis, ω is the speed of rotation about the reference axis, and Δt is the time between samples. *k* indicates that the data is from the current sample and *k-1* indicates the previous sample (if a faster sample rate is needed or the processor is needed to perform other functions, the time step can be increased or decreased accordingly). Determining ω requires the gyro outputs and knowledge of the current pose of the vessel and the complete coordinate transformation between the vessel coordinates and the world coordinates. The angle that this equation provides is the angle that results between a body-fixed reference frame and an earth-fixed reference frame. For example, if the roll gyro produced a signal that resulted in an angle of 3°, the z-axis of the vessel would be 3° offset from the *z* axis of the inertial frame (the *Down* axis). When the signals from all the gyros are accounted for, along with the complete coordinate transformation, the knowledge of each of the angles would result in an understanding of the overall orientation of the vessel.

This theory seems sound, but experimental results with these sensors demonstrated that further investigation would be necessary before an accurate analysis of the vessel's orientation would be possible based on the output of these sensors. The primary shortcoming of this theory has to do with the properties of the integration process. Essentially, the average value of the signal over a known period of time is weighted according to the length of that time span and added to the previous value of position. For highly accurate measurements, that would be a successful design. However, these sensors produced a large amount of noise. Although the NavBoard was stationary, the output from the sensors would be nonzero. If the values were evenly distributed between positive and negative rotations, the net effect would be to negate each other. However, experimentation showed that the noise would be biased to one direction despite a bias-reduction process conducted at the initialization of the NavBoard (Figure 11). A filter was

coded into the software which successfully eliminated much of the drift during static testing (Figure 12). The weakness of this filter was that the more noise was eliminated, the more valid high-frequency information was lost.

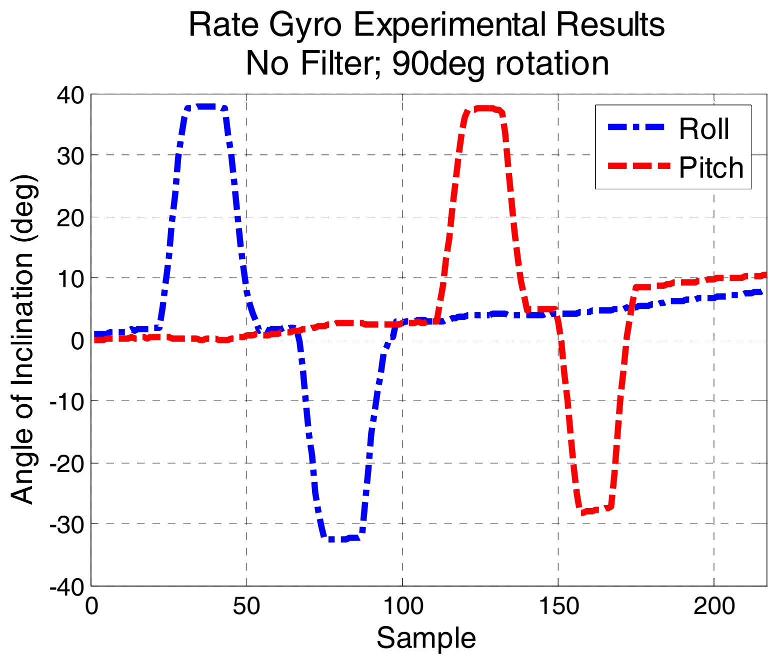

Figure 11: Rate gyro data showing drift after integration

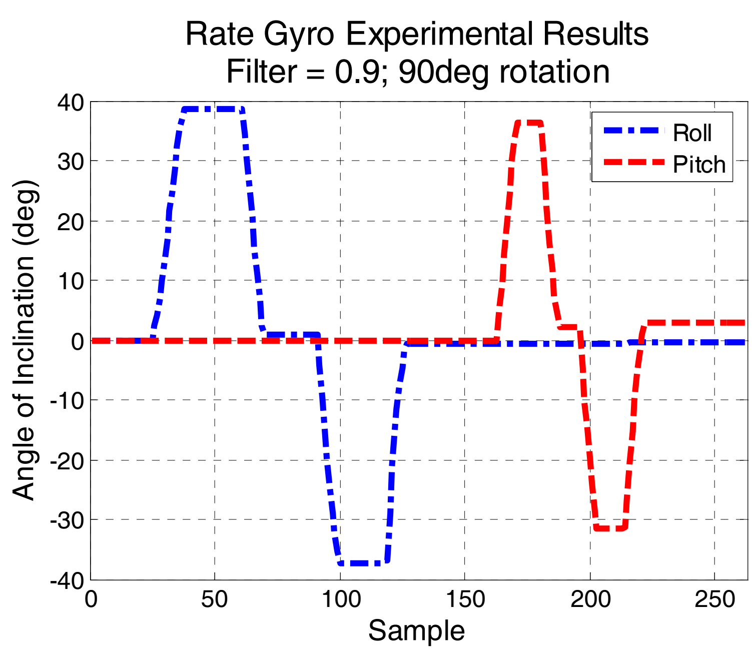

Figure 12: Gyro integration data with filter applied showing reduced drift

As a result of these efforts, it was determined that further refinement or redesign of these sensors would be necessary before they could be considered reliable in navigational applications. Initial efforts were made, and the value of the output was increased significantly as a result of the integration process. The gyros were valuable as a means of tuning the sensors and gaining an understanding of the vessel's performance, but they were not used as part of the navigational strategy, as the vessel was operating in displacement mode. In displacement mode, the pitch and roll dynamics of the vessel are generally neglected from a control perspective [5], so complete functionality of these sensors was not of critical importance for the objective of this research. Note, however, that this sensing capability is a crucial component of the measurement suite for follow-on studies, and represent a significant outcome of the project.

4.4. Accelerometer

If the orientation of the vessel were accurately known, it would be possible to develop the redundant position sensing system. Although signal processing limitations prevented the full implementation of such a system, the hardware was completely developed. The final sensor that would be necessary for this system was an accelerometer, an instrument that measures the amount of acceleration it experiences in a certain direction. The MMA7260Q provides three-axis acceleration information for the microprocessor. It has variable measurement ranges of +/- 1.5 g, 3.0 g, and 6.0 g. The highest sensitivity is at the smallest range, where it increments 800 mV/g [16]. This sensor provides the linear acceleration readings on each of the three axes of motion. It was bench-tested and properly calibrated to output 1 g on each axis for static tests (Figure 13).

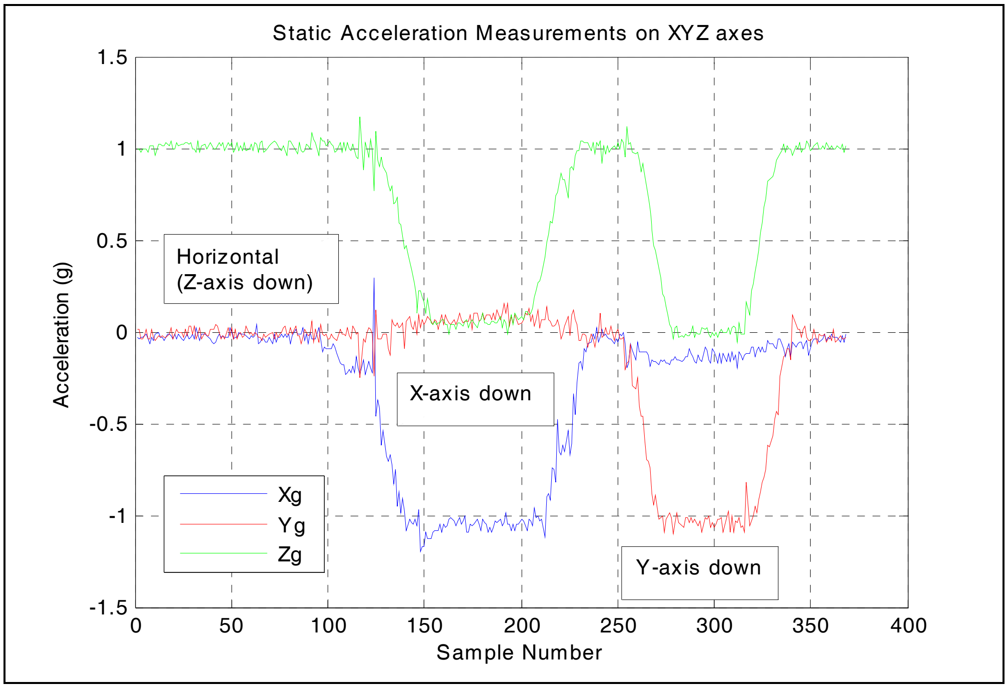

Figure 13: Results from Static Tests of the Accelerometer

In addition to providing static acceleration data, this sensor was designed to provide information about acceleration as a result of the motion of the vessel. However, there were significant limitations on the value of the data from this sensor recorded during open water tests of the vessel. Figure 13 shows that, although the sensor produces the proper output, it also displays a small amount of noise. These measurements were taken while the NavBoard was in a stable, controlled environment. During the actual testing of the vessel, the environment was subject to a great deal of vibration from the motor as well as other electrical signals, and the signal was characterized by a much greater amount of noise (Figure 14).

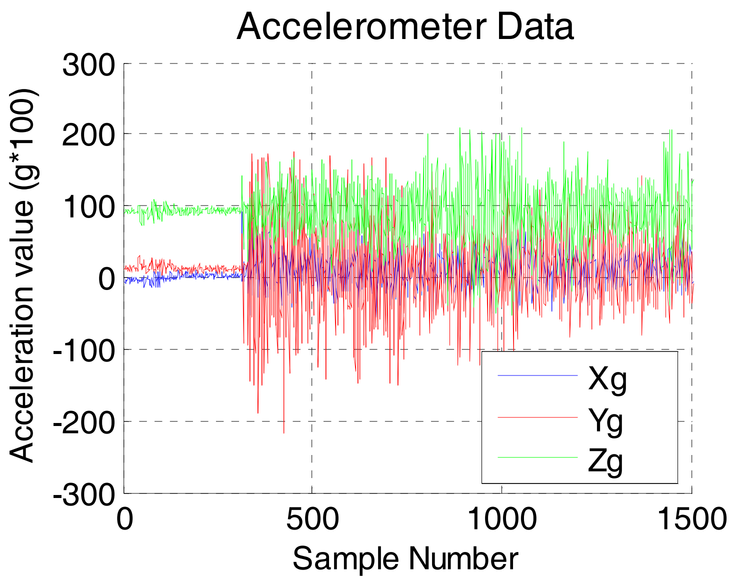

Figure 14: Accelerometer output showing the effects of vibration on the system

In this condition, the signal was not of great value. Possible solutions to this dilemma include dampening the sensor and shielding it from other electronic sources. Also, applying electronic filters to the output signal could also serve to drastically reduce the noise read by the NavBoard. These modifications would make the sensor more useful for the navigational scheme, and would form the first step in follow-on studies. Again, this sensing capability is a key component of the design, but the successful integration of this sensor into the suite as well as the initial observations of the functionality serve as foundational contributions for further exploration.

4.5. Inertial Navigation System

Two information sets, one from the gyros and one from the accelerometer, are necessary in order to facilitate an inertial navigation system, or INS, by which the full coordinate transformation between the vessel and an inertial reference frame can be generated. This system would provide the vessel with position and orientation information based solely on internal

readings of the motion of the vessel. Since acceleration readings come as a result of gravity as well as motion, it is necessary to decouple these factors. In order to do that, the orientation of the vessel must be known, which highlights the significance of the rate gyros. For example, if the orientation is determined to be normal in accordance with an earth-fixed inertial reference frame, the expected output of the accelerometer is 1 *g* on the z-axis and zero on the others. If, in that orientation, the x-axis outputs 1 *g*, then that signal can be correctly interpreted as linear acceleration. The vessel is normal to the surface of the earth and accelerating at 9.81 m/s^2 across the water. If the orientation were not known, there would be no way to tell the difference between 1 *g* of linear acceleration and 1 *g* of static acceleration which would result from the vessel being rotated so it is standing up on end. After the initial position and velocity is known, linear acceleration signals can be integrated to produce linear velocity and ultimately position information. With these necessary sensors mounted on the NavBoard, a position sensing system largely independent from the GPS receiver can be achieved.

The results of the tests of the inertial sensors, as discussed, demonstrated that while the hardware was fully functional, additional signal processing would be required before the data could be reasonably expected to contain enough accuracy to be considered for use as navigational information. The data from these sensors were collected throughout the testing process in order to prove the functionality of the hardware and provide a starting point for further analysis and signal processing, but the navigational strategy was not based on inertial information. In fact, such additional information proves to be of little value when the vessel is operating in displacement mode.

4.6. Range Sensors

In addition to knowledge of its location, the autonomous controller needs information about the location of other objects around the vessel. There are different techniques currently in use for obstacle detection in air, including sophisticated radar and vision systems, infrared devices, and sonic devices. The platform itself is too small to handle a radar system, and a vision system refined enough to use for this application would be expensive and difficult to operate. Infrared devices generally have a shorter range than is required for this system. Therefore, the ideal sensor for obstacle detection seemed to be an ultrasonic ranging device. The Devantech SRF-08 was chosen for this application.

The SRF-08 had several qualities that made it appear to be useful. Its specified range of up to 6 m [17] would be more than enough range for the vessel to be able to safely maneuver away from an obstacle after detection. It was small enough (Figure 15) that it could be mounted on the hull without significantly weighing it down or altering its buoyancy characteristics. It was able to communicate directly with the Rabbit 3000 on the NavBoard, which would greatly simplify the implementation process. The sensors are able to operate using different settings for maximum range, maximum analog gain, and return measurements in different units.

Each of these variables has significant implications for the operation of the sensors. Since the range measurements depend on an elapsed time between sending and receiving a signal, the maximum range of the device is controlled by limiting the sample rate. However, if the sample rate is too fast, echoes from previous samples can be registered during subsequent sampling periods, confusing the data. Reducing the maximum analog gain for the sensor can compensate for this phenomenon. This gain value multiplies the signal returning to the sensor, so a smaller gain will result in a smaller measurement signal. If the signal is to reach the

detection threshold, a smaller gain would require a larger signal. In this way, weak echoes can be tuned out of the system. Additionally, the sensor is able to return measurements in values of inches, centimeters, or milliseconds. All of these features seemed useful for the final design of the obstacle detection system, so this sensor was selected for a testing and tuning process to prepare it for integration into the system.

Figure 15: Devantech SRF-08 Ultrasonic Ranging Sensor

After the sensor was successfully integrated into the NavBoard so that communication with the Rabbit was established, tests were run to determine its functionality. The initial tests were basic but they revealed a significant flaw. An object was placed at preset distances from the sensor while the sensor was placed close to the ground. The object was to determine the actual range of the sensor under conditions similar to those it would experience during operation. At close range, the SRF-08 was highly accurate, but when the object was farther than approximately 40 in from the sensor, the sensor would not detect it (Figure 16). This was a significant problem because a range of 40 in would not be enough to allow the vessel to maneuver around a potential hazard. One possible explanation for this performance flaw was that the sensor was detecting the ground at that point. Since the sensor was on a short mounting device, this was a reasonable conclusion. However, the same performance was demonstrated when the sensor was placed at the edge of a table, farther than 40 in from the ground. Other

modifications were made to the arrangement of the hardware, such as inclining the sensor itself, but nothing was able to correct the malfunction.

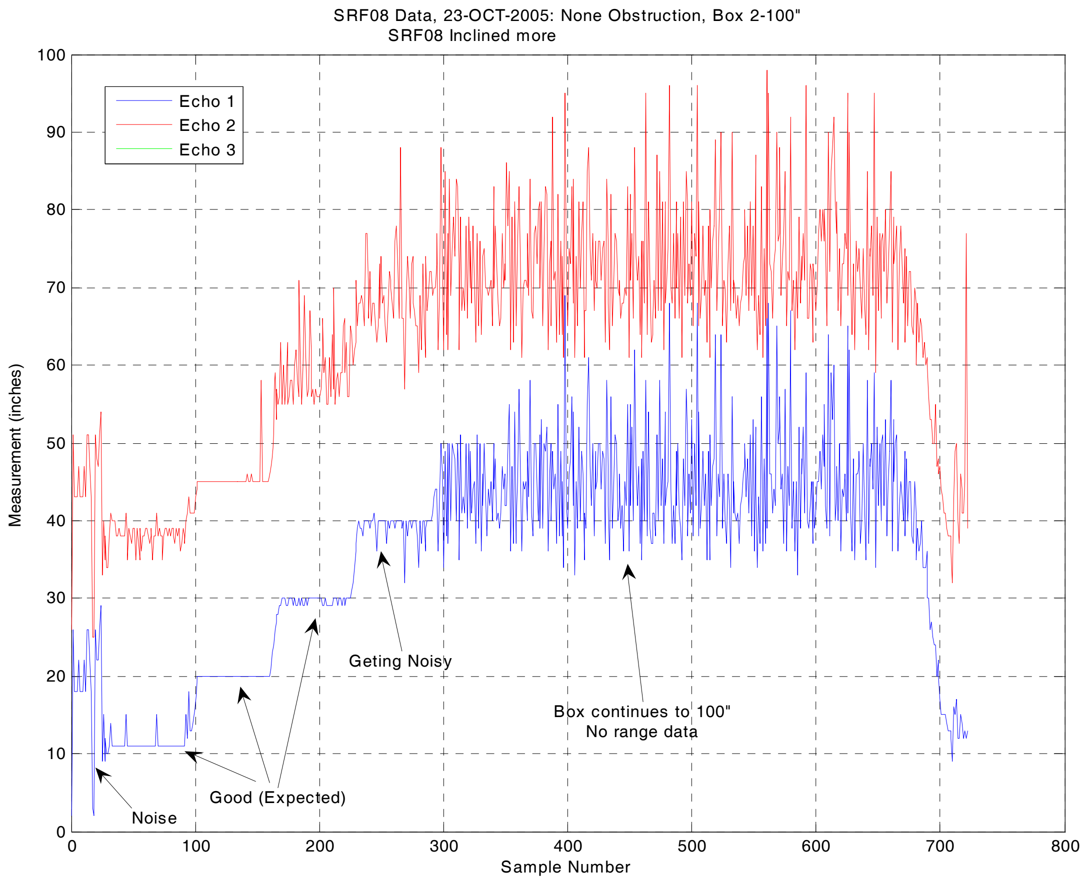

Figure 16: Detection stops near 40 in

The problem was finally found to be a flaw in the software provided to give the microprocessor the ability to operate the sensors at a most basic level. The Systems Engineering Department provides such algorithms for use in student design projects. These basic algorithms have generally been tested and proven over the course of many semesters. However, this was the first application of the SRF-08, so no one had successfully implemented the sensor previously. The software had been written to operate the sensor in its default state, which was a maximum range of 11 m, a maximum gain of 1025, and the value of the measurement in inches. The

problem was that the gain was so high that the sensor would register even a slight amount of noise. If there were no object within 1 m (40 in), the noise was great enough to register as the dominant echo, instead of the object. After the code was modified to limit the gain, useful measurements were possible up to 4 m from the sensor (Figure 17).

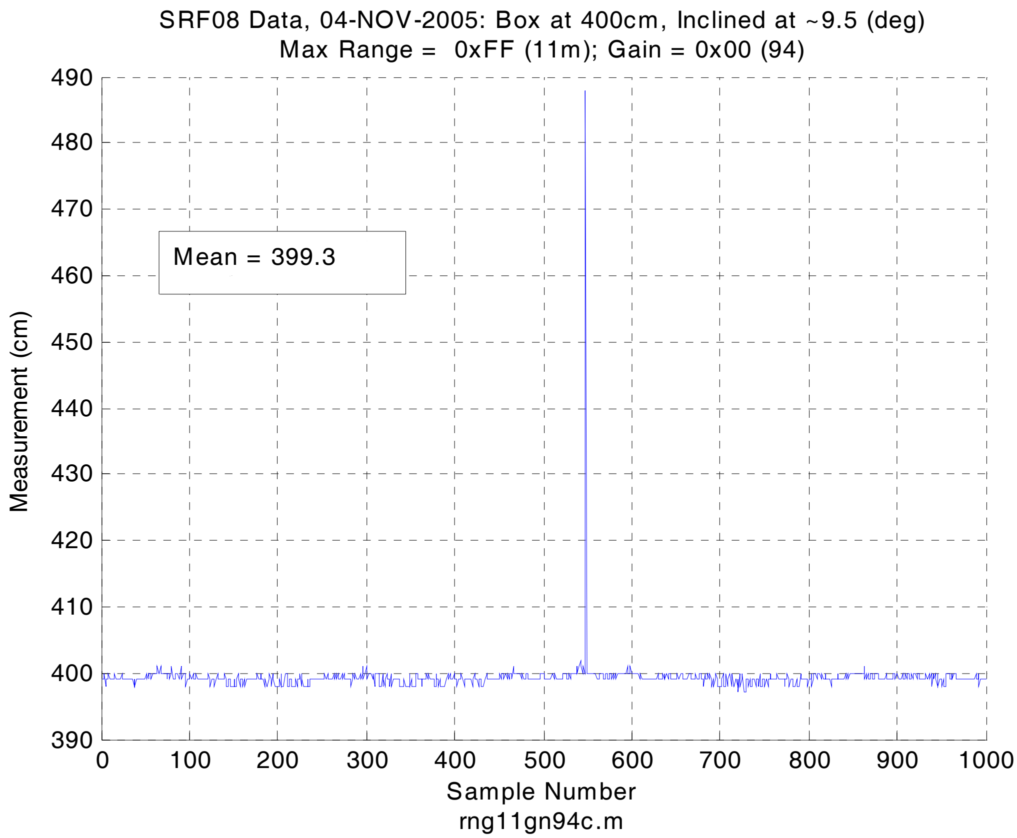

Figure 17: Detection at 4m

Once the sensor was functioning properly, experiments were conducted to determine the ideal orientation and settings for the sensor. It had already been noted that proximity of the ground in relation to the sensor's position had a significant impact on the effectiveness of the sensor, so it would be useful to orient the sensor in such a way as to limit this effect. The vertical placement of the sensor would be limited due to the adverse effect that raising the center of gravity of a vessel has on its stability. The other option was to incline the sensors so that the

bottom of the spectrum would not reflect off the "ground" - or sea surface - during normal operations at close range. At a certain inclination, however, the sensor began to overlook significant objects, so it was necessary to find an inclination between the two extremes. Several trials were run and an angle of 9.5° was determined to be effective. It was also necessary to determine the horizontal spread of the spectrum in order to determine how far to offset the sensors. The documented spread pattern showed the majority of the signal emitted directly forward of the sensor, while still showing a moderate peripheral spread (Figure 18). The SRF-08 was able to detect objects up to 30° off center at a distance of 1 m, 18° off center at a 2 m distance, and by 3m, the object had to be in line with the sensor to be detected (Figure 19). Finally, tests were run to determine the effect that reflections off of water would have on the sensor, since all the testing to this point had been over land. It was found that calm water had less effect than flat ground; the sensor was able to take readings up to 5 m over water with no inclination (Figure 20).

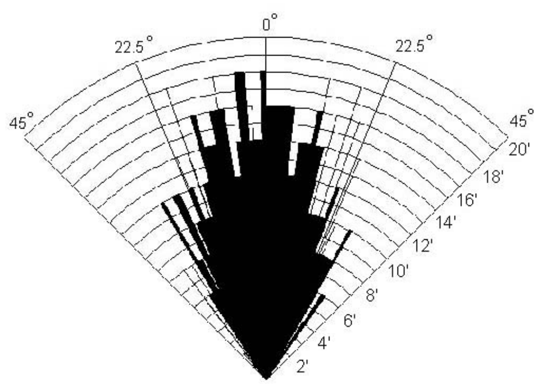

Figure 18: Specified spread pattern [18]

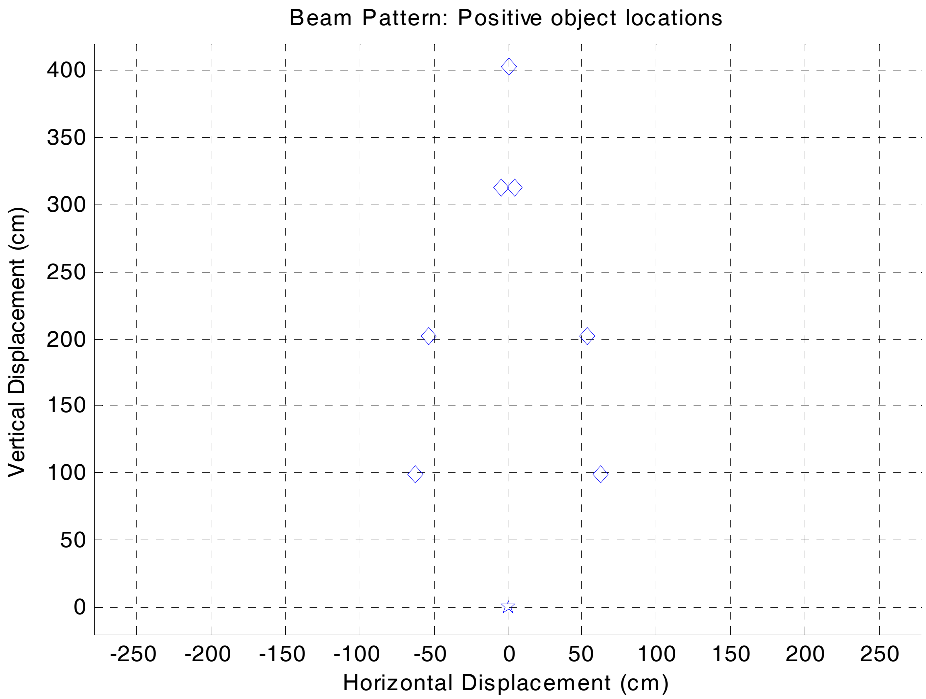

Figure 19: Experimentally determined detection range

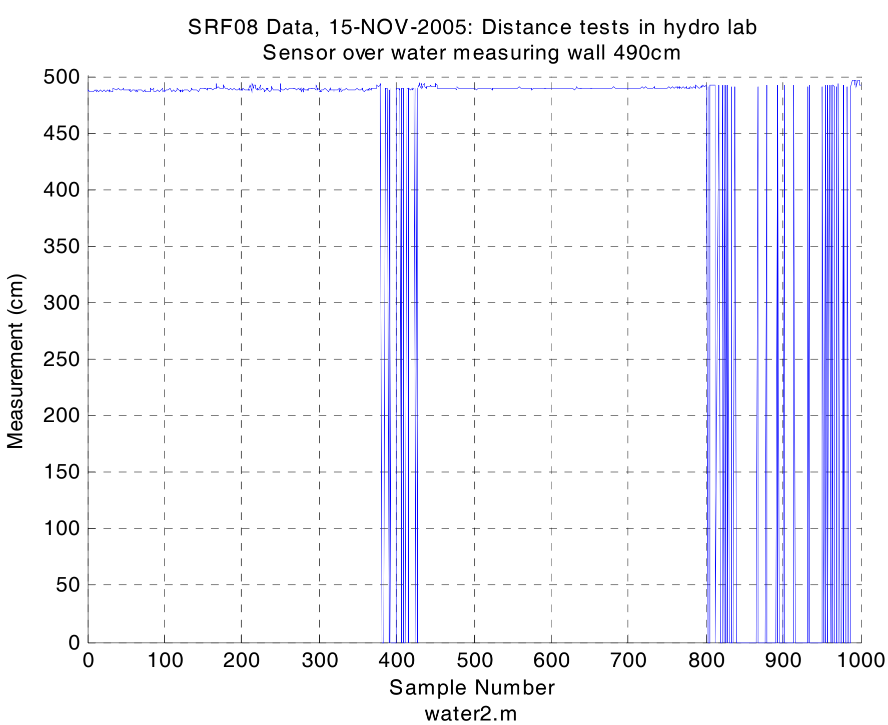

Figure 20: Extended range over water

This information served as the basis for the design of a mounting apparatus for the ranging sensors. The initial plan was to mount three sensors on a single bracket, which would be mounted on a servo. This installation design would allow the whole sensor suite to scan the surface of the water in search of potential hazards. The sensors could search in the direction of a turn in order to ensure that the turn would be safe and clear before the actual command was given. Different materials were tested which could be used to enclose the sensors in a protective, watertight casing on this bracket, but the SRF-08 was not able to take measurements through either clear packing tape or a thin sheet of Plexiglas. Since the sensors could not be completely enclosed, a splashguard was mounted under the sensors to prevent spray from hitting them. The disadvantage of this arrangement was that the sensors would be immersed in water if the vessel capsized, but during normal operation they would stay dry. It was not expected that the conditions on the Severn River would frequently be such that would cause the vessel to capsize, so this disadvantage was determined to not be a significant problem. Additionally, the cost of replacing the sensors on the rare occasion that an accident would occur was not significant enough to deter this design strategy.

4.7. Sensor Pod Design

Based on these plans, a mounting system was constructed for the range sensors. The theory behind this design was to create a system that would both protect the ranging sensors and the camera from the environment as well as facilitate the scanning needs of the sensors. This was the first complete hardware construction process conducted during this research, so there was a great deal of discovery during this portion of the project.

4.7.1. Design Criteria

A number of considerations were made during the initial design process for the sensor pod. It was necessary that this mounting system be able to rotate to allow the range sensors to scan in different directions. The cables for the range sensors and the power cord for the camera had to be run from below the deck of the vessel to the pod. These two criteria were highly dependent on one another. There were a few options for rotating the sensor pod. Initial designs employed a telescoping system where a shaft fixed to the pod rotated inside a shaft fixed to the hull. These shafts would be hollow so that the cables could pass within them. This design was disregarded, however, when the weight of such a system was fully realized.

Refinements on that design led to a lighter system that involved a central rotating shaft which would bear the weight of the pod vertically, but was supported by fixed rods which would reduce the torque on the base of the shaft. For this design, the question became whether to mount the main shaft directly onto a servomotor or to gear it so that the motor did not have to directly bear the weight of the system. While this was being considered, the separate question of the cables was also pondered. A simple solution seemed to be to run the cables freely from the pod to a hole in the deck and to enclose them in some sort of flexible, lightweight tubing that would protect them from the elements. There were no foreseeable problems with this idea, so it would serve as the tentative plan for connecting the sensors to the processor.

To this point, it was accepted that the shaft would have to rotate because the servomotor that would produce the rotation had to be mounted below decks to keep the center of gravity low, and thereby increasing stability. When this theory was more closely considered, however, other factors came into view. The added complexity of a rotating system was leading to excess weight which could adversely affect stability of the vessel more significantly than the weight of a single

servomotor. At this point, a single fixed shaft was considered. The servomotor would be mounted in the sensor pod, which would be free to rotate around a single shaft that was firmly fixed to the keel of the vessel. This system seemed to emphasize simplicity and reduce weight, which were both appealing features of the design.

The pod had to be watertight, but it would also be necessary to gain access to the sensors inside in case maintenance or adjustments were required. There had to be enough room inside the pod so that the cables could be connected to the sensors without interfering with each other, although the overall weight of the pod was an issue and additional volume generally means additional weight due to the increased surface area.

4.7.2. Fabrication Process

These considerations led to a basic understanding of the overall design scheme. At this point, measurements were taken to ensure that the pod was large enough to mount all of the necessary sensors and accompanying cables but not too large because more surface area meant more weight. The final design had a width of 6.5 in, a depth of 3.5 in, and was 2.5 in tall. This proved to be enough space for the three range sensors, the wireless camera, the servomotor, and all the cables that were housed in the pod.

Once the overall dimensions of the pod were understood, fabrication began. Based on the results of previous testing with the range sensors, and offset angle of 15° between each sensor was desired (Figure 21). In order to maintain strength and integrity in the Plexiglas used for construction, the front plate of the pod was heat molded. A wooden cast was made with the 15° angles prepared. A strip of Plexiglas was heated so that it was malleable and then placed on the mold. When it cooled, it had the corners and angles that were necessary for the front plate of the pod. This piece would cover the front and both sides of the pod. The remaining faces of the pod

were cut from flat sheets of Plexiglas. The top and bottom were cut from 1/8-inch Plexiglas instead of the 1/16-inch sheet that was used for the sides because added strength was desired. It was important that the corners of these pieces be rounded off because sharp corners increase the tendency of a piece of Plexiglas to fracture.

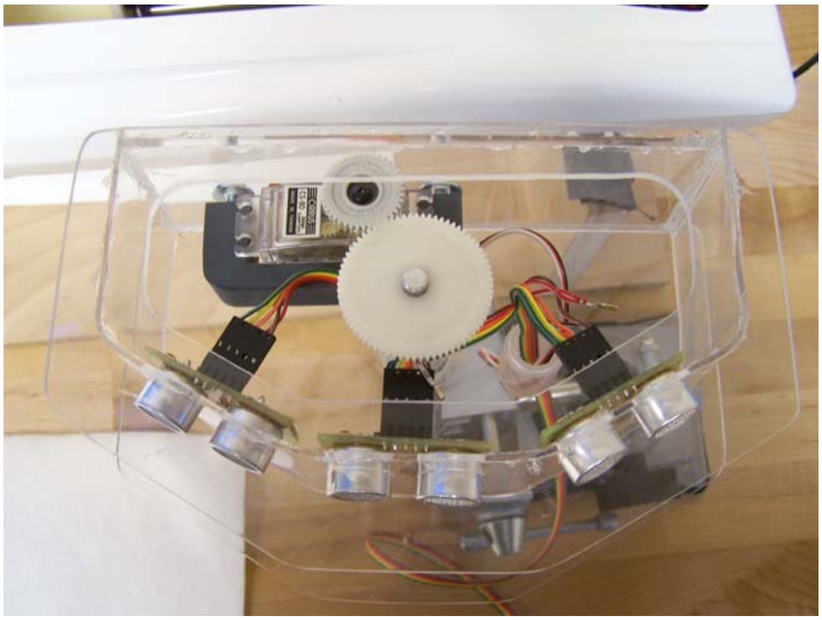

Figure 21: Sensor pod showing range sensor offsets

When the pieces of the pod were formed, the process of fitting them together began. The first step was to make all the fixtures that would be used to mount the sensors, motor, and rotational system. It has been found that the range sensors are not effective through Plexiglas, so they were to be mounted with the transmitters and receivers pushed through holes in the front of the pod. Since Plexiglas does have a tendency to fracture, a traditional drill would not be practical for producing holes in the sheets. Instead, a die grinder was used, which is a pneumatic device that uses a spinning abrasive tip to gradually remove material from the sheet until a hole is formed. To mount the range sensors, a template was made on a flat piece of Plexiglas which was then traced onto the three front faces of the molded front piece. A small hole was made and

then slowly expanded with the grinder until the range sensors would all fit in place. When the final adjustments were made, these sensors would be glued in place, sealing the holes around them.

This same technique was used for all the holes to be made; two in the bottom for the support shaft and the cables and two in the back for mounting the motor bracket. A large hole was made in the top of the pod so that the sensors could be accessed once the pod was completed. Since this was a significantly larger hole, a slightly different technique was used. Once a hole was started with the die grinder, a jigsaw was used to remove a large portion of that piece. It was then sanded so that the interior corners were smooth. A cover was fashioned that would be taped into place to maintain watertight integrity.

The design of the rotational support system was complicated. The aluminum shaft was cut and a smaller diameter rod was firmly attached to the end. Then, a piece of Plexiglas rod was carefully drilled out to fit around the narrow extension of the shaft. This Plexiglas piece was glued to the bottom plate of the sensor pod. The narrow shaft extended through the end of the Plexiglas collar for a gear to be fixed upon. This was to hold the pod in place as well as to provide a mechanism for a servomotor to turn against. The motor was fixed against the back wall of the pod using a bracket which is tightened in place with two bolts. Adhesive rubber strips serve to shim the motor away from the wall and provide a tight fit when the bracket is engaged. The gear on top of the servomotor meshes with the gear on the end of the fixed rod, allowing the pod to rotate as desired.

To complete the design, the shaft had to be fixed to the boat itself. Two holes perforated the deck, one for the shaft and one for the cables. In order to attach the shaft to the hull in such a way that it would be removable as necessary, two separate attachment pieces were fabricated.

The main piece was fashioned to fit to the keel of the vessel and be glued in place. There was a hole in the center for the shaft to rest in, and a set screw to ensure the shaft remained in place. A second piece was made to glue to the underside of the deck to provide additional lateral support for the system. With these pieces in place (Figure 22), the sensor pod was fixed in position and the range sensors were tested.

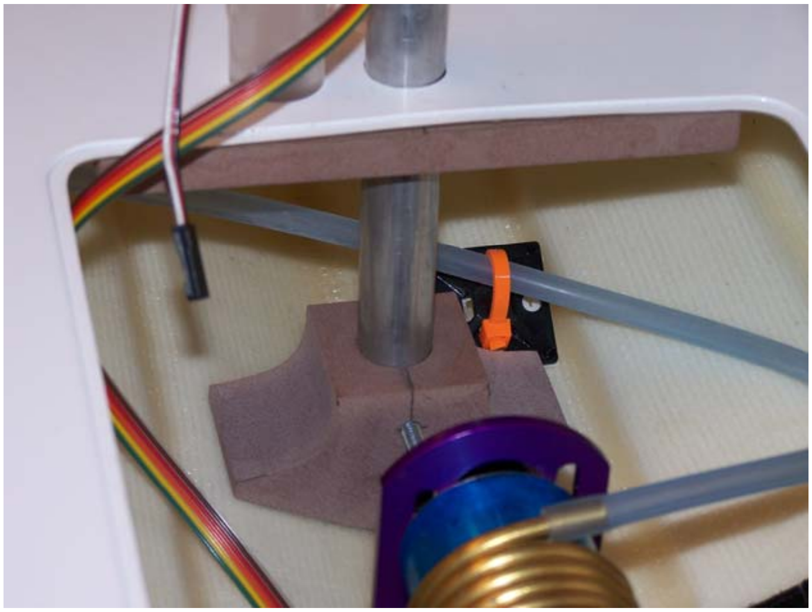

Figure 22: Sensor pod mounting hardware

At this point, a significant dilemma in the project was reached. Although the sensors had been refined so that they were able to reliably measure up to 4 m, when they were installed in the sensor pod, they were only able to measure up to 1 m. There were a number of possibilities for this phenomenon, and all were investigated. One possibility was that the pod itself was affecting the signals that were reaching the receivers. The sensors were removed from the pod and tested again, but the readings were still only up to 1 m.

A second consideration was that some of the settings had changed on the sensors. The sensors communicate with the central microprocessor using IIC logic, which is useful because

multiple sensors can be attached to the processor on the same communication line because they each can have a unique address. Part of the mounting procedure had included readdressing the individual sensors so that they could communicate effectively and not interfere with one another on the data line. If settings had been changed during this readdressing process, the output of the sensors would be affected. However, the maximum range and gain settings were carefully checked and they were identical to the optimal settings that had been previously determined. The settings were then modified to see if the performance could be improved, but this process was not successful.

A final correctable factor that was considered was the possibility that the proximity of the sensors with one another was causing destructive interference. If the transmissions from one sensor were being received by another sensor, the measurements would be ineffective. In order to test this possibility, sensors were removed from the system so that only one was operating at a time. Again, this did not change the single sensor. It would not register values greater than 1 m. These investigations suggest that the sensors were damaged during the construction, wiring and testing process, resulting in higher noise levels and therefore more limited maximum range (lower sensitivity).

As a result of these investigations, it was determined that full-scale obstacle avoidance would not be possible with the current sensors. Further investigation could identify a more robust sensor or discover the source of the drastic performance change of these sensors, but this investigation was not possible over the course of this research. However, a proof-of-concept obstacle avoidance system was developed. Since the range measurements were not large enough to allow the vessel to respond under actual operating conditions, the theory behind this system was tested under more controlled circumstances.

The basic obstacle avoidance plan was simple. The range sensors were arranged in such a way that if an obstacle were present in front of the vessel, it would be detected by the sensors. If it came within a certain range, the vessel would modify its course in order to avoid a collision. When the obstacle was no longer detected, the vessel would resume tracking towards the next waypoint. Although this process could not be tested over water, the concept could be proven on land. Tests were conducted where an object was placed in front of the sensors close enough that it would register under the reduced range capabilities of the sensors. The response of the rudder was monitored to determine if the correct reaction occurred. These tests were qualitatively successful since the rudder responded as intended. When an object was placed to the right of the vessel, the rudder turned so the vessel would turn left. If an object were to the left or in front of the vessel, the rudder would guide the vessel to the right. The obstacle avoidance algorithm guided the vessel to the right in case of a central obstacle because the vessel dynamics show that it has a smaller turning radius to the right, so emergency maneuvers were designed to favor that direction. Although full-scale tests of the obstacle avoidance system were not possible due to the untimely failure of the range sensors, the basic concept was demonstrated to be effective using controlled tests under laboratory conditions.

4.8. Wireless Camera

The final sensor to be added to the system was a wireless camera. This camera was mounted inside the sensor pod so it was completely protected from the elements. In order to ensure that the vessel operates safely at all times, it was necessary to develop a system to provide real-time feedback about the vessel. One of the simplest ways to accomplish this was to use a camera to send video to a base station. The PrymeSecurity ALM-2451G (Figure 23) is a stand-alone wireless camera. There is a processor and transmitter mounted directly to the camera, so

there is no need to integrate the camera with any of the other microprocessors. With a 9V power supply, the camera is able to produce and send live video to a receiver. The signal is then intended to be sent to a laptop computer. The system has been tested indoors to have a range of slightly over 100 m. The outdoor range is stated to be approximately 300 m [19] if there is a line of sight between the transmitter and receiver. This camera enables the operator to have constant knowledge about the condition of the vessel even if the vessel is out of sight. This is an important ability because, if the controller malfunctions, the operator will still be able to override the signal from a remote control and prevent an accident or possible destruction of the vessel.

Figure 23: PrymeSecurity ALM-2451G [20]

4.9. Sensor Design Conclusions

In order for an autonomous controller to be able to function, it needs feedback from appropriate sensors. Therefore, sensor selection is an important step in any autonomous system design. In addition to basic navigational capabilities, the sensors used for this system were intended to have the capability to determine the vessel's global position, local orientation, and acceleration. Any obstacles that may stand in the way of the vessel were to be detected, and the system could be safely monitored from a distance. These capabilities provided the vessel with

the potential for highly advanced control processes, and were more than sufficient for the needs of this research.

The initial results from the GPS receiver were not satisfactory, and investigations into the causes of the poor performance proved fruitful. As a result of a significant refinement process, the GPS output was improved. With an effective GPS receiver, the data that were measured were critical in the navigational routine. The signals from the GPS receiver provided the controller with ample information to make the necessary guidance decisions.

Challenges were also met with each of the remaining sensors, and the direct results were not as successful. However, significant contributions were made. The hardware was, in every case, functional and integrated with the NavBoard. Additional work will be necessary before the data streams will be useful for more complex identification or for high-speed control, but the data were effective in the specific application of this research. Possible sources of the poor performance of the sensors were investigated. In some cases, these investigations revealed the actual source of the problem. Other investigations eliminated some factors as possible causes of the performance problems so that they provide a firm foundation for additional work to begin. Such future work could focus on modifying the obstacle avoidance sensors in order to improve their performance, as well as improving the data processing strategies to improve the results from the other sensors.

The sensor suite and NavBoard system, as designed, meet the requirements for the two missions for which they were intended. As demonstrated in a later chapter, the sensors provided sufficiently accurate feedback data for autonomous navigation, and have the capability to provide data streams for further study of the vessel dynamics in follow-on efforts.

5. Microprocessors

All of the sensors in the previous section, with the exception of the wireless camera, require some sort of separate processor to initialize and operate them. This processor serves as the means of storing and manipulating any data that is received from the sensors. In addition to operating sensors and storing data, a processor is necessary to provide proper control signals to the motors and the speed control system on the vessel. The Rabbit 3000 was integrated into the NavBoard for the purpose of operating the sensors. In order to control the actuators, an Innovation First EDU-RC microprocessor was included in the system. These two microprocessors serve as the computational core of the ASV.

5.1. Rabbit 3000

The Rabbit was integral to the successful operation of the NavBoard. It was mounted directly to the board (Figure 24) and permanent connections were made with all the sensors, with the exception of the ranging sensors. It was designed to receive data from the sensors, process that data, and output it in a form which would be useful for the control system. In order to accomplish this, software was written.

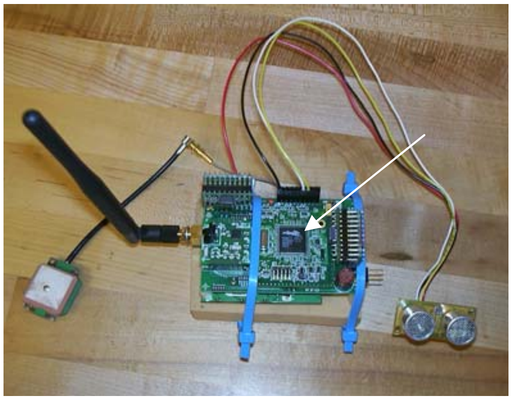

Figure 24: Rabbit 3000 at the center of the NavBoard

The Rabbit operates in an environment which is similar to the computer language *C*. Following the completion of the design of the NavBoard, a program was written that gave the NavBoard basic functionality. This code enabled the Rabbit to initialize and sample from all the sensors. These basic functions were useful to become initially familiar with the sensors on the NavBoard, but more advanced software would be necessary. Over the course of this research, the software was refined and modified so that any future users of the NavBoard would be equipped with a substantially enhanced performance package.

Without modification, the software was able to sample the sensors and receive data. However, there was little consideration made for processing those data. Some of the sensors required calibration, which was not complete. An example of this has to do with the accelerometer. This sensor was not functioning properly during the early stages of testing. The readings from the z-axis in particular were confusing, sometimes behaving as if that output was coupled with that of the other axes. In the end, this problem was due to an error in the calibration process. When the sensor was initialized, all of the axes were set so that the value they output at that instant was zero. This was done to create a starting point for future readings. It is a logical procedure because when the system is initialized it is generally at rest with a normal orientation. However, in this orientation the z-axis should read 1 *g*, not zero. Although this seems like an obvious statement, it was more difficult to realize that this was the problem using the actual system. Once the problem was identified, it was a matter of modifying the code to initialize the accelerometer properly. This was completed, and the sensor now outputs expected data.

Another major modification of the code had to do with the implementation of the range sensor into the system. It was designed as a peripheral sensor because it would usually be

physically separated from the board. The NavBoard was equipped with pins that could be used to facilitate communication with such peripheral devices. However, the skeleton code for the NavBoard did not include functions that would generate this communication. Instead, the basic code for the range sensor was added to the NavBoard program. Modifications had to be made to facilitate communication between the sensor, which uses IIC logic, and the serial port of the Rabbit. After this was complete, the sensor was able to take readings and send them to the processor. This was when the problem with the gain and range settings was discovered and corrected.

Many tests were conducted on the range sensor in order to determine the optimal settings for this application. This began as a tedious and inefficient process involving copying and pasting data from the sensor output into MATLAB to perform the necessary numerical manipulations. After a few of these tests were conducted, it was determined that there had to be a more efficient method to capture this data. Two major modifications were made in order to facilitate this streamlining process. The first change was to save the results of the range samples in large arrays and print those arrays at the end of the entire sampling period. This was done in order to reduce the amount of time that the sampling process would take. In addition, MATLAB commands were displayed around the arrays. At the end of the program, these commands and the arrays were printed so that the display resembled a MATLAB script file. The second modification had less to do with the actual code and more to do with the programming environment. Dynamic C 7.32SE has the ability to log the STDIO window to a file. The STDIO window is where any print commands are displayed, such as the MATLAB commands and the arrays. When the command was given to save those results as an .m file (used by MATLAB), the data was automatically in a form that was directly usable in MATLAB for data analysis.

These modifications greatly increased the speed with which tests could be run on the range sensor.

All of the sensor refinement processes involved similar software modification processes. The effectiveness of the different sensors depended to a large degree on the validity of the software that was used to operate those sensors. As a result, the code that was loaded onto the NavBoard was modified frequently and the performance of the board was continuously improved. One of the problems with this process, however, was that the memory limit of the microprocessor was soon reached. In order to successfully compile the software, many of the functions within the code had to be transferred to what the processor referred to as “xmem.” This is a section of memory on the Rabbit that is not as easily accessible as the standard memory locations, but allows for increased storage space of the main program. After these modifications were made, there was enough memory for the sensor operations and ultimately the large control routine.

5.2. Innovation First EDU-RC

The Rabbit 3000 is well-suited for the operation of sensors, but it is not as easy to integrate with motors as the Innovation First EDU-RC (Figure 25). Further, the computational and I/O burdens already placed on the Rabbit made it difficult to implement control and sensing on that device without overburdening the processor. As such, the EDU-RC was used for both user interface and for control of the actuators. This microprocessor was designed to be used directly with motors in robotics applications. Used primarily in remote controlled systems, this microprocessor has output pins that communicate directly with motors. However, while the remote controlled option is an important safety feature, this system will operate autonomously. Therefore, in addition to being able to send commands to the actuators, this microprocessor has

to be able to receive those commands from the appropriate source, whether that be a user or an autonomous controller.

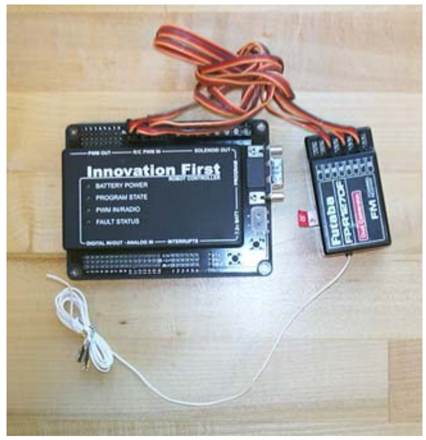

Figure 25: Innovation First EDU-RC

This microprocessor also had the responsibility of increasing the safety of operating the vessel through *fly-by-wire*. In a *fly-by-wire* system, user commands are passed through a computer, which interprets both the desired action and the state of the system to determine appropriate actuation commands. Anti-lock braking systems are, effectively, fly-by-wire, and the F/A-18 Super Hornet relies on a fly-by-wire system to achieve extremely high performance.

Certain performance characteristics of the ASV were observed during initial testing that made a fly-by-wire system worthwhile. In addition to increasing the safety of the vessel operation, this system allowed for a basic verification of possible autonomous control of the vessel because a microprocessor was making decisions about the actual output to the actuators.

When observing the initial test runs, it was noticed that small inputs on the controls would result in a large swings in output from the motor. Since most of the research for this project was to be conducted at low speeds, this throttle range had to be scaled to be more useful. Additionally, when a reverse command was given, the high speed of the propeller had a tendency

to pull the stern of the vessel down into the water rather than moving the vessel backwards. The vessel capsized as a result of this phenomenon.

Compensating for these two conditions served as the motivation for the fly-by-wire system. The first step was to scale the throttle input so that it was limited to a more useful range. This was accomplished by removing the offset voltage from the input voltage and then multiplying that value by the desired percent of maximum throttle. Then, the offset voltage is added back to the scaled value to command the desired throttle setting. The other part of the process was to limit the rate of acceleration of the propeller. Basically, if the desired throttle command was too much larger than the current throttle command, it was only allowed to increase by a certain step size each iteration until it finally reached the desired throttle setting. However, since it is desirable to be able to stop as quickly as possible, the throttle was only limited in the forward direction.

These modifications allow the vessel to operate more safely than it could otherwise, and the speed is now easier to control. Additionally, these modifications were made so that the acceleration limitation is active at all times, but the maximum throttle limitation is only active when a switch is set. Although it is a simple example, this switch process is analogous to receiving data from the sensors. If an obstacle is detected within a certain range, it would be like flipping a switch from normal operation to obstacle avoidance operation. In this way, it is reasonable to understand how the sensor data will be used to facilitate autonomous navigation.

Further along in the research process, a second fly-by-wire system was developed. In this case, the desired outcome was a precise throttle control system. When testing the maneuvering characteristics of the vessel, it was desirable to be able to associate certain speeds of the vessel with the throttle setting. Using the remote control without any computational assistance was not

accurate enough for this testing because the joystick-based throttle commands could not be increased in small enough increments, nor were such commands repeatable. To overcome this dilemma, a routine was written that allowed the throttle setting to be precisely controlled. Each complete deflection of the throttle in the forward direction resulted in a single positive increment of the throttle setting, and the reverse for the negative direction. This allowed tests to be run where the exact throttle setting was known so that the maneuverability characteristics of the vessel could be observed.

5.3. TTL Communications

Adding a second microprocessor to the system significantly complicated an already complex environment, so it had to be absolutely critical in order to be considered. In addition to the limitations on the Rabbit functionality which have already been discussed, there were a number of other issues that made the EDU-RC necessary. Primarily, many of the communication ports were being used to operate the sensors and the wireless modem, so there were not enough available to control the operational portions of the vessel itself. Additionally, providing power to those motors would have placed a significant drain on the power supply to the Rabbit, which could cause unwelcome responses if the sensor data became corrupt. Finally, the coding that would be required to operate the motors would have been complicated and required a significant amount of time to produce. It would place additional computational requirements on the microprocessor which already had a large number of responsibilities and limited memory available.

The EDU-RC microprocessor was able to easily overcome a number of those problems. It is designed with a number of ports dedicated solely for output to different motors. There were more than enough for the needs of this project. It also uses a separate power supply, so the

power for the Rabbit could be focused on operating the sensors. The primary feature of the EDU-RC microprocessor was the simplicity involved with writing the software to control the motors. Each output pin has a dedicated variable preset for it, so that particular outputs can be modified by simple equalities. This functionality would prove particularly useful when commands were sent from the Rabbit. However, communication between the two microprocessors would not be a simple procedure.

5.3.1. TTL Background

Since a second microprocessor was determined to be necessary, a strategy for communication had to be developed. The solution was in the Transistor-Transistor Logic (TTL) ports that were common between both microprocessors. These ports operated using the same protocols, so it would not be necessary to program complicated handshaking processes into the software.

A TTL line is a serial communication line which passes information through a signal which takes the form of a series of high and low voltages. The transmitting end of the line creates a series of highs and lows which stands for whatever information is being sent. The receiving end is able to reconstruct that same signal and interpret the original information. Each unit has a transmit and a receive pin so that simultaneous communication is possible, although it was not necessary for this particular research since information was only traveling from the Rabbit to the EDU-RC. This basic concept would serve as the premise for communication between the two microprocessors.

5.3.2. Initial Testing

The first step towards establishing positive communication between the microprocessors was to establish that the individual TTL ports were functional. This was a more complicated process for the receiver than it was for the transmitter because the data line from the transmitter could be measured using an oscilloscope. For the receiver, it was necessary to program a test scenario that would display the data that it received in order to verify functionality. This process was simplified by a piece of software that was available on the Innovation First website [21]. This software was designed so that the data being transmitted were displayed on the computer screen next to whatever data were being received. The operator was required to connect the transmit and receive pins, and the port was deemed functional if the input and the output were the same. This testing process showed that the TTL port on the EDU-RC board was functioning properly.

The process of testing the transmission pin of the Rabbit required monitoring the output on an oscilloscope to verify that there was data being transmitted and that it was the correct data. Although this process demonstrated that the port worked, a possible dilemma was discovered. Standard TTL signals oscillate between 0 V and 5 V. The high signals from the Rabbit, however, were shown on the oscilloscope as 3.3 V. These voltage levels are significant because the differentiation between high and low pulses is how the data is understood by the microprocessors. While most receivers would be able to correctly identify this voltage level as a high pulse, it would be safer to receive a high signal of 5 V.

A voltage buffer circuit was designed to solve this problem. A SN74HCT245N Octal Bus Transceiver has the ability to receive signals at one voltage level and transmit that same signal at a different voltage level [22]. It has multiple pins which each serve different purposes,

such as an input voltage, a ground pin, and multiple transmit and receive pins. There are also pins that serve as switches to determine the chip's mode of operation. By applying a constant high voltage to these pins, the buffer was always set in the desired mode to transmit a received signal at the supplied voltage. The supply pin was connected to a 5 V source, so whatever 3.3 V signal was input from the Rabbit was mirrored in a 5 V signal sent to the EDU-RC. This buffer proved to be an effective solution to the voltage discrepancy, and soon the EDU-RC was able to recognize that the Rabbit was sending a signal.

5.3.3. Software Requirements

Since a signal was being sent and received, it was now necessary to make sure that the signal was significant for the operation of the vessel. Significant additions to both the Rabbit and the EDU-RC software were necessary before this was to occur. The Rabbit software received the initial attention so that the actual signal that was being sent could be finely tuned and understood, which would make it possible to then modify the reception algorithm. Once the port was opened at the correct baud rate of 19200, it was possible to start sending information. It was necessary to understand exactly what type of information could be sent over the TTL line. When a piece of data (a character) was sent out of the TTL port, it was converted to an integral number which stands for that character according to ASCII standards. For example, the letter "t" is represented by the number 116. Since there were only a limited number of commands that would be sent to the EDU-RC, there were only a few values of interest. There were three motors that needed to be controlled: the rudder servomotor, the sensor pod servomotor, and the speed controller for the main throttle. Each of those was given a particular code of 'r', 'p', or 't', respectively. This character was transmitted and then followed immediately by the specific parameter desired for that motor. Conveniently, the EDU-RC performs speed and motor control

using values of 0 – 255, exactly corresponding the range of values from a single character transmission on a TTL line. Thus, if a neutral throttle setting of 127 was desired, the character "t" was sent, followed by the character "127." Since the ASCII code for "t" is actually 116, the actual sentence was "116 127." This same process was followed for the other actuators so that the Rabbit was able to direct the EDU-RC on how to direct those motors.

Knowledge of the transmitted sentence allowed for accurate translation by the EDU-RC. After the data passed through the buffer, it was received by the TTL port. The EDU-RC was set up to look for three specific codes, 112, 114, and 116, which stand for 'p', 'r', and 't'. If one of those values was received, the EDU-RC knew that the next value sent would be the value to assign to the designated motor. For example, when the neutral throttle command was given, the 116 indicated that a throttle setting was about to be sent, and when the 127 character was received, it was converted to an integer value and assigned to the output pin for the speed controller. In this way, each of the actuators on the vessel could be operated by the EDU-RC based on guidance from the Rabbit.

5.3.4. TTL Results

In order to test these algorithms before the actual control code was running, a separate piece of software was written for the Rabbit which would allow the user to input either of the motor identifiers on the keyboard followed by the desired setting of the motor. If a key was hit besides 'p', 'r', or 't', no action would be taken. Once one of those keys was hit, however, the operator was prompted to input a value for that particular motor, and that value was then transmitted to the EDU-RC. The input and output of the buffer was monitored on the oscilloscope to verify that the voltage shift worked properly. The output pins of the EDU-RC were connected to test motors, and the commands from the keyboard successfully operated those

motors. This verified that the signals sent as a result of the control calculations would be understood and acted on by the EDU-RC in order to achieve vessel mobility.

5.4. Microprocessor Conclusions

There was a great deal of software development involved with implementation of this system. Two processors were used because of the different advantages they possess. The Rabbit 3000 communicates well with many different sensors, and the EDU-RC integrates smoothly with motors and operator commands through standard R/C interfaces. These processors provide the vessel with the computing power it needs to conduct autonomous navigation. Once communication was established between these two microprocessors, progress could be made toward autonomous navigation.

6. Path Planning

In order for the controller to be able to direct the vessel, it must have a desired path to follow. This path can be manually selected by placing waypoints between the initial and desired final position but this process would involve an operator, reducing the level of autonomy of the vessel. Also, this process must be redone for each different starting and ending point, which would be inefficient. Therefore, it was necessary to develop a process by which the system could chose waypoints for itself based on existing knowledge of the local waterways. This would not be enough, however, because transient and uncharted obstacles would require path replanning at a local level. Two different strategies were developed to address these concerns. The first, known as approximate cell decomposition (ACD), was used to develop an overall scheme for reaching the endpoint. The artificial potential field (APF) approach was designed to be used to maneuver around obstacles. The unique capabilities of these two processes complement each other in such a way that a successful navigational strategy could be developed.

6.1. Approximate Cell Decomposition

It is reasonable to expect an operator to be able to equip an autonomous vehicle with a desired destination and a basic map of the local area. From this information, it would be necessary for the vehicle to decide how to travel from its current location to the final destination without incident with any permanent obstacles. Approximate Cell Decomposition (ACD) is one method of determining a suitable path. As the name implies, this process decomposes the given map into cells in consecutively smaller increments until a channel with only empty cells, an E-channel [23], is found. Once this channel is found, a path can be developed. This path then serves as the basis for the commands sent to the controller.

Before the decomposition process can begin, the initial and final positions must be known, as well as any large, fixed obstacles and terrain to consider. Once these parameters are known, the region of interest is broken into quadrants. Each quadrant is investigated and labeled either as empty, mixed, or full. An empty space has no portion of its area occupied by any obstruction, a full space has no portion without obstruction, and a mixed space has a combination of obstruction and free space.

Once a space is labeled either empty or full, it is set aside. All mixed spaces are then decomposed a second time into quadrants, and the process is repeated. Of particular interest are the cells containing the initial and final positions. Once these cells are designated as empty, it is possible for an E-channel to exist. Beginning at the cell containing the initial position, each tangent cell is queried as to its designation. If it is empty, it is marked as a potential path. Once all cells tangent to the initial cell are queried, the process repeats for each tangent cell. This process continues iteratively until either the final position is reached or there are no more tangent empty cells. If the latter occurs, the mixed cells are again decomposed and the tangent search process repeats. This process continues as necessary until an E-channel is successfully located.

Applying this strategy to the waters surrounding the Naval Academy presented some interesting challenges. The first step was to enter a graphical representation of the seawall into MATLAB, which would serve as the default set of obstacles for the cell decomposition. Using data from www.maptech.com, the coordinates of different points around the Academy were recorded. These coordinates were entered into matrices and plotted, and the plot showed the seawall (Figure 26.g). Once this plot was completed, the E-channel would be evaluated to determine the GPS coordinates used by the ASV. Using different initial and final points, the decomposition process was run on this space with mixed results. If the initial and final positions

were both in open water, the process was effective. However, if either position was in any sort of restricted water, such as the Santee Basin or College Creek, the number of iterations was large enough so that the computational power required to complete the decompositions and calculate adjacencies was too great under the limitations of MATLAB (the computing software selected for the base station that transmitted the path to the vessel and collected the transmitted date from the NavBoard for later analysis).

The solution to this problem was to set up conditions that would limit the number of required decompositions. One way to do this was to focus on the intricate portions of the waterways and address them separately. In addition to the overall seawall picture, spatial representations of the Santee Basin and College Creek were developed (Figure 26.a,h). For each, a point was located outside the smaller body of water that would serve as either a start or end point, depending on whether the vessel was going into or out of the body. Because the space was focused on the restricted body, it was possible to develop an E-channel with a relatively small amount of decompositions. The endpoint of a transition out of a restricted body served as the starting point for a decomposition process in the main body. If the vessel was required to transition back into a restricted body, the path in the main body would end at the starting point for the restricted body, thereby forming a continuous path to the objective. With this iterative process in place, it was possible to develop E-channels into and out of restricted bodies of water without causing the processor to malfunction. The waypoints generated by the decomposition would serve as the waypoints sought by the autonomous controller.

The following example shows an ACD process from a point in the Santee Basin to a point in College Creek. The initial map of Santee Basin is divided into quarters (Figure 26.b). Since there is not yet empty space, the process is repeated. After the third decomposition, both

the initial and final points are in empty space (Figure 26.c), so a tangent search is conducted (Figure 26.d). Since this search reveals that there is no E-channel available, a fourth decomposition is conducted, a tangent search is begun (Figure 26.e), and a path is found (Figure 26.f). The final point of that path is the initial point for the next ACD of the smaller scale map (Figure 26.g), and that final point serves as the initial point for the journey into College Creek (Figure 26.h). This example demonstrates how the iterative process of ACD can be used for complex navigational problems.

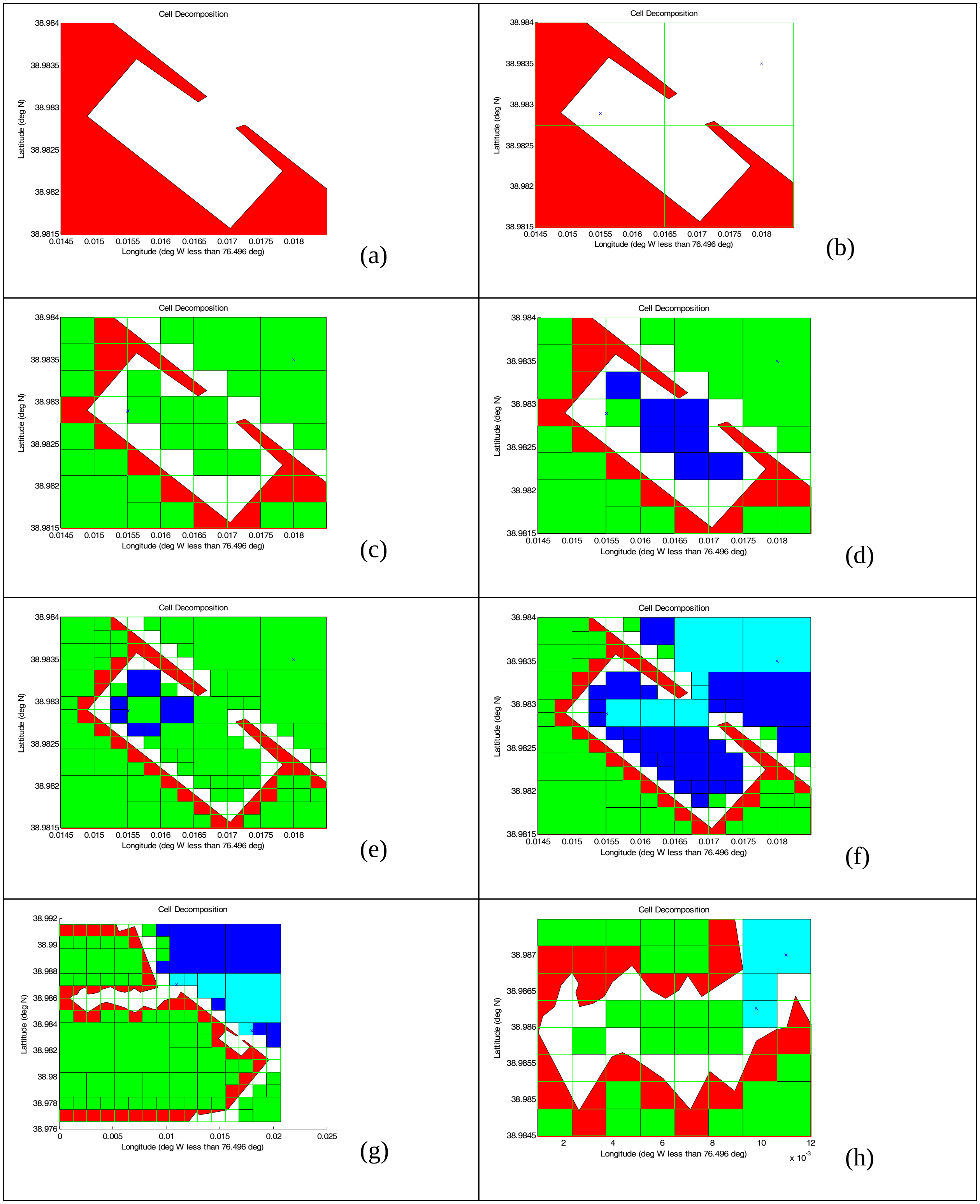

Figure 26: ACD Process

This process was adopted for use in the final testing of the vessel. These tests were conducted in College Creek and a portion of the Severn River immediately outside the mouth of the creek. To create the map that served for this decomposition process, the actual GPS receiver on the NavBoard was used to develop a series of points that would serve as the boundary of the test area. This was done to ensure that any inherent drift in the sensor would be accounted for in the decomposition process and a safe path would be generated. In addition, the location of the desired destination was measured and input to the decomposition algorithm so that the process always ended at that location. The decomposition was conducted and a series of waypoints were generated, which were coded into the navigational controller on the vessel. Although the aspect ratio is not correct so that the area of the map covered by water is maximized (Figure 27), shows the intended path of the vessel as computed by the ACD process.

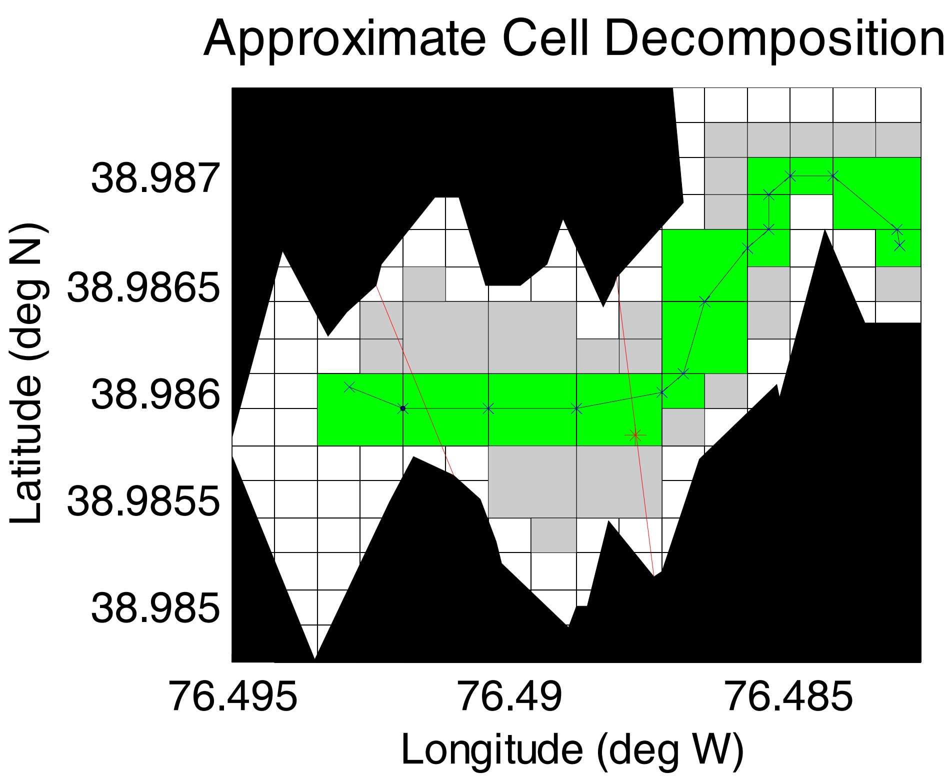

Figure 27: ACD process showing desired track with waypoints

6.2. Artificial Potential Fields

The weakness of the ACD process is that it requires a great amount of time and processing capacity to operate, and will not operate if too many decompositions are required. If ACD were required anytime a minor course correction had to be made due to an obstruction, the autonomous navigation would be a slow process. More significantly, there was no way to compensate for obstacles that were not included in the map. For these reasons, it was desirable to incorporate a second process to facilitate navigation around obstacles. Artificial Potential Fields (APF) was determined to be well suited for local path replanning.

Under the APF path planning approach, potential fields are created across the space of concern and the vessel follows the gradient of the field, with a global minimum at the target point. The endpoint creates an attractive force, drawing the vessel towards itself. Obstacles create repulsive forces. The vessel is controlled by following a combination of these forces, which is the gradient of the potential field. If the vessel comes too close to an obstacle, it is instructed to change course (Figure 28). It will continue on a course to avoid the object until it no longer detects the object in the path between itself and the objective. At that point, the attractive force of the destination takes over and the vessel continues to the target. In this manner, the vessel will traverse from waypoint to waypoint, each time being drawn to the next destination.

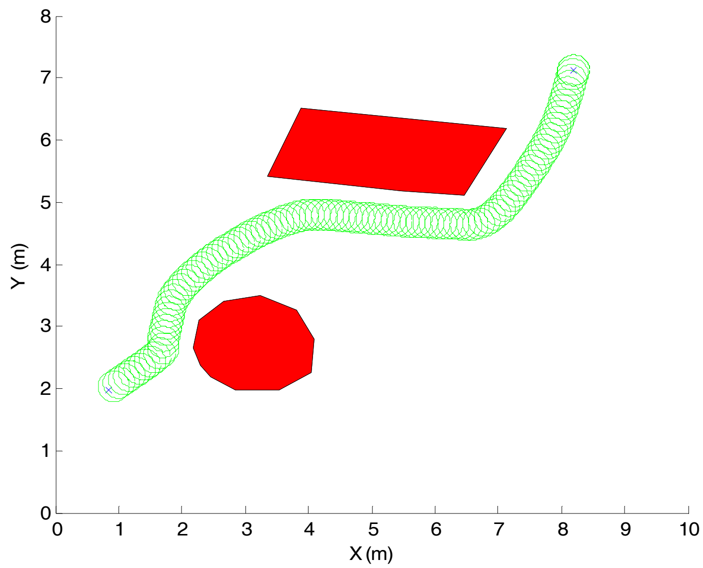

Figure 28: Successful APF navigation

The APF method also has a significant limitation. It is possible for the vessel to be drawn into an area from which it would not be able to find its way out. This is known as a local minimum. If the vessel were tracking towards the destination and came upon an obstacle that was not in the initial ACD map, it would alter its course to follow the edge of the obstacle until it was clear. If that obstacle had a bend in it that placed it in front of the vessel, it would be repulsed from that as well. There would be repulsive forces on both sides, and the attractive force would continue to draw it forward. It would seem as if there were nowhere to go (Figure 29). This phenomenon can be overcome by programming certain responses if this event should occur. A simple solution would be for the vessel to follow the object clockwise until a clear path is determined. This process would not be suitable for path planning across complex terrain, but it is appropriate for avoiding the types of obstacles that will normally be encountered by the vessel such as buoys, pilings, and other vessels. Integrating these two path planning strategies

would allow the vessel to effectively travel to its destination while avoiding unforeseen obstacles that may be in the way.

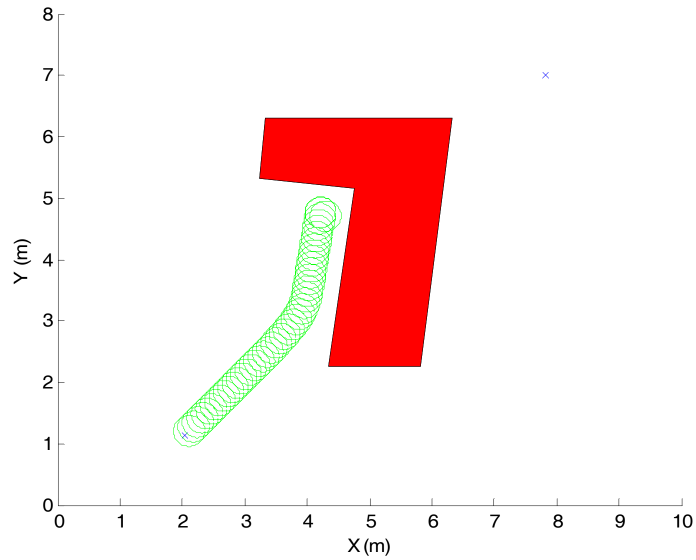

Figure 29: Local minimum

The final design did not actually include a formal manifestation of the APF process. Instead, the theory behind the process was instituted without the complex calculations required by the different fields. The strategy (covered in more depth in the sequel) was for the vessel to travel toward each consecutive waypoint. If, during the course of that travel an obstacle was detected, the vessel would alter course accordingly. Once that obstacle was no longer in range, the waypoint tracking process would resume. Although this is not mathematically identical to the formal APF strategy, the concept is similar and it produces similar results. An understanding of the APF process was necessary in order to fully design the current navigational strategy.

6.3. Path Planning Conclusions

The combination of these two processes, ACD and APF, allows for the successful determination of a desired path and the ability to modify that path should obstacles be

encountered that were not part of the original ACD map. Both of these techniques are important for autonomous navigation, and each process is especially well suited for its portion of the problem. The adoption of the APF concepts into a simpler strategy greatly reduced the processing requirements for the navigation system. With these processes in place, the autonomous controller was prepared to use the sensor suite to gather the necessary data in order to begin autonomous travel.

7. Modeling

A controller is a mathematical equation that determines the amount of correction that needs to be made for different amounts of error in a system. It is manifested in the form of equations that are implemented on a physical system, and are designed to achieve desired performance characteristics. A mathematical model of the system is necessary in order to design a controller. This mathematical model describes how the physical system responds to different inputs, which is necessary information when determining how much input the system needs to correct for different amounts of error. Therefore, before a controller could be designed for this system, a mathematical model needed to be developed. The controller in this application is a maneuvering controller – to work in conjunction with the path planning and obstacle avoidance algorithms.

While some systems are easy to model, other systems are so complex that they simply cannot be modeled accurately. Surface vessels are among the more difficult types of vessels to model because of the variable terrain on which they operate. They move in three dimensions with six degrees of freedom, which is similar to subsurface and aerial vehicles. However, in the vertical direction surface vehicles are largely at the mercy of the water. They are primarily able to control their lateral motion, analogous to most land vehicles. The complexity is compounded by the fact that a surface vessel exhibits different maneuvering characteristics based on the orientation of the vessel, partly due to the shapes of the submerged and exposed portions of the vessel.

Despite the complexity of the surface vessel systems, models have been created which reasonably accurately describe the motion of different types of surface vessels. Most of the research in this field is associated with large commercial vessels, but many of the results of this

research can be applied to smaller vessels if careful attention is paid to the assumptions made in the development of the large scale model. Large ships are not generally significantly affected by sea surface waves, so heave is typically ignored in the existing models (see Table 1 for an overview of vessel motions). Also, roll and pitch are frequently neglected because these motions do not generally significantly affect the maneuvering performance of large ships under normal operation, and they tend to be highly damped. This leaves a basic model to include the effects of surge, sway, and yaw.

A number of models were investigated over the course of this research, including the Nomoto model, a separate three degree-of-freedom (DOF) model, and an experimentation-based maneuvering model. Initially, the Nomoto and the three DOF models were promising candidates for use in the final controller design. However, as hydrodynamic testing was conducted, the response characteristics of the vessel were noticed to be such that complex models were not necessary for moderate-speed maneuvers. Due to the small size of the vessel, it was able to respond quickly and accurately to inputs, so an alternative modeling strategy was pursued and successfully employed. This strategy involved relating the turning rate of the vessel with the rudder setting that achieved that turning rate. With this relationship, the final heading controller was developed. In the following sections, a full analysis of the various models and a discussion of the testing methods and data collected are presented.

7.1. Nomoto Model

The Nomoto model [24] was based off of a four degree of freedom model. This model is complex, with coefficients that are difficult to determine, so a simplification was necessary so that the model would be more readily useful. In order to simplify the model, the roll motion was neglected. This simplification should be validated through simulation, but it is generally

acceptable because roll is less significant than yaw, surge, and sway, and tends to be an unactuated degree of freedom. The result of this simplification is the 2nd order Nomoto model [24]:

$$\frac{r}{\delta} = \frac{K\left(1+T_3 s\right)}{\left(1+T_1 s\right)\left(1+T_2 s\right)} \tag{2}$$

This transfer function (a method of relating the output of a system to a given input), relates the yaw rate *r* to the rudder angle *δ*. *s* is the Laplace representation of the time variable. For this equation, *K* is known as the static yaw rate gain, which is basically a constant which indicates how fast the vessel will turn for different rudder angles. T_1, T_2, and T_3 are time constants for the system. These constants describe how fast the system would respond to different inputs. In state-space form, which is a representation of the same information as a transfer function in matrix form, the model is as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{3}$$

$$\begin{aligned} x &= \begin{bmatrix} v \\ r \\ \Psi \end{bmatrix} \\ u &= \delta \\ y &= \Psi \end{aligned} \tag{4}$$

$$\begin{aligned} A &= \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix} \\ B &= \begin{bmatrix} b_{11} \\ b_{21} \\ 0 \end{bmatrix} \\ C &= \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{5}$$

In this case, v is the sway speed and Ψ is the vessel's heading. The gain and the time constants from the transfer function are represented by the state matrices *A* and *B*. The values for the coefficients of these matrices are as follows:

$$\begin{aligned}
a_{11} &= \frac{\left(I_z - N_{\dot{r}}\right)Y_v + Y_{\dot{r}}N_v}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}} \\
a_{12} &= \frac{\left(I_z - N_{\dot{r}}\right)\left(Y_v - mu_0\right) + Y_{\dot{r}}N_r}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}} \\
a_{21} &= \frac{\left(m - Y_{\dot{v}}\right)N_v + N_{\dot{v}}Y_v}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}} \\
a_{22} &= \frac{\left(m - Y_{\dot{v}}\right)N_r + N_{\dot{v}}\left(Y_v - mu_0\right)}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}} \\
b_{11} &= \frac{\left(I_z - N_{\dot{r}}\right)Y_\delta + Y_{\dot{r}}N_\delta}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}} \\
b_{11} &= \frac{\left(m - Y_{\dot{v}}\right)N_\delta + N_{\dot{v}}N_\delta}{\left(m - Y_{\dot{v}}\right)\left(I_z - N_{\dot{r}}\right) - N_{\dot{v}}Y_{\dot{r}}}
\end{aligned} \tag{6}$$

For these coefficients, I_z is the moment of inertia around the Z-axis. N_r, N_v, Y_r, etc. are different hydrodynamic coefficients that must be determined for the vessel. The mass of the vessel is indicated by m, and u_0 is the reference speed.

Even after this simplification, these coefficients are complicated and require a great deal of calculation and experimentation to determine. For simplicity, this model has been further reduced to the 1st order Nomoto model:

$$\frac{r}{\delta} = \frac{K}{\left(1 + T \cdot s\right)} \tag{7}$$

This reduction is particularly valid when the value of T_1 is similar to the value of T_2. When this is the case, the zero term in the numerator cancels one of the poles in the denominator. Since T_1 and T_2 are rarely exactly equal, T is defined as:

$$T = T_1 + T_2 - T_3$$

This definition increases the applicability of this model. Still, it is most accurate in cases where the two time constants are determined to be similar. In state-space form, this model becomes:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{8}$$

$$\begin{aligned} x &= \begin{bmatrix} \Psi \\ r \end{bmatrix} \\ u &= \delta \\ y &= \Psi \end{aligned} \tag{9}$$

$$\begin{aligned} A &= \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{T} \end{bmatrix} \\ B &= \begin{bmatrix} 0 \\ K/T \end{bmatrix} \\ C &= \begin{bmatrix} 1 & 0 \end{bmatrix} \end{aligned} \tag{10}$$

This is a much simpler version than the 2nd order model, which means that the amount of experimentation necessary for determining the parameters of the model will be significantly less. It is also a reasonably accurate model for certain conditions, so was a candidate for selection for this research.

7.2. Three Degree of Freedom Horizontal Model

The second model that has been widely used is a different three degree of freedom model which accounts for horizontal motion [5]. The model is presented as follows:

$$\begin{aligned} \dot{\eta} &= R(\psi)\upsilon \\ M\dot{\upsilon} + D\upsilon &= \tau \end{aligned} \tag{11}$$

$$\tau = Bu \tag{12}$$

$$\upsilon = \begin{bmatrix} u & v & r \end{bmatrix}^{\mathrm{T}}$$
$$\eta = \begin{bmatrix} n & e & \psi \end{bmatrix}^{\mathrm{T}} \tag{13}$$

$$R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_g - Y_{\dot{r}} \\ 0 & mx_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{15}$$

$$D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \tag{16}$$

In this model, *u*, *v*, and *r* appear as velocity terms for surge, sway, and heave, respectively. *n*, *e*, and Ψ are the vessel's rotational positions roll, pitch, and yaw, respectively. The remainder of the coefficients are recognizable as some of the same from the Nomoto model. This model is simplified with assumptions based on linearity, which means that the model is suited for low speed applications. This will be the case for the majority of the testing, so this model also had potential.

7.3. Coefficient Determination

Although a simplified model was ultimately chosen as the basis for the control design for this research, an experimentation process was undertaken in order to provide valuable information should a refined control design be required in the future. In fact, this model was discovered as a result of parts of this experimentation process. Choosing a commercially available hull as the test bed for this research simplified the research process in many ways. The research and effort that would be required for a hull design were avoided and a great deal of time

was saved. The disadvantage of this process was that detailed hull geometry as well as hydrostatic and hydrodynamic performance parameters were not known. Therefore all of the coefficients for these models had to be determined. There were a few ways to determine the values for the coefficients. Since these models have been designed for applicability over a wide spectrum of vessels, the coefficients within the different matrices are intended to be experimentally determined or estimated for specific vessels. There are different methods for conducting this testing. These methods include conventional maneuverability tests in a tow tank, open water maneuvering tests, as well as numerical calculations based on the shape and dimensions of the hull. Different techniques were employed on this vessel in order to determine the coefficients to use in the selected model.

The primary method used for determining maneuverability parameters during this research was a series of open water maneuvering tests. Characteristics such as the turning radius and slalom ability are significant in determining many of the coefficients. These values are particularly useful because they are based on actual maneuvers of the vessel on the actual terrain where the controller will be operating. The motion of the vessel is governed by the same actuators that will drive it during regular operation, so the results of these tests were particularly informative.

Experience with modeling many different types of hulls has demonstrated that reasonably accurate estimates can be made for the coefficients based simply on the shape and some important parameters of the vessel. Numerical models have been developed which are able to take these values and calculate a set of hydrodynamic coefficients, which can then be input to the model matrices. This technique can be used independently to develop the model of the system,

but for this research it was used in conjunction with the various experimental techniques in order to most accurately represent the system.

This experimentation process required multiple tools and testing areas. The first step was to determine the detailed geometry of the vessel's hullform. That data were then evaluated using analysis software to produce a number of important hydrostatic values. These values, when combined with the results of inclining tests conducted in the USNA Hydromechanics Laboratory (HydroLab) ballast tank, produced the necessary values for the estimation of model coefficients. Tests were also conducted in the HydroLab's 120 ft towing tank to develop the relationship between motor setting and speed. The final tests that were conducted took place in the HydroLab's 380 ft towing tank, where open water maneuverability tests were performed and the relationship between rudder setting and turning radius was derived.

To begin, dimensional measurements were taken using the CNC mill (Figure 30). The hull was inverted and fixed on the base of the mill. At 2-inch intervals, the three-axis coordinates of a series of points from the side of the hull to the keel was measured and recorded to form a series of frames of the bottom of the hull. These points were input to a Rhino file and a computer-generated surface was developed (Figure 31). Rhino is a three-dimensional modeling program frequently used in vessel modeling applications. This information was necessary to computationally determine many of the hydrostatic characteristics of the vessel used to determine the hydrodynamic coefficients.

Figure 30: CNC Mill testing

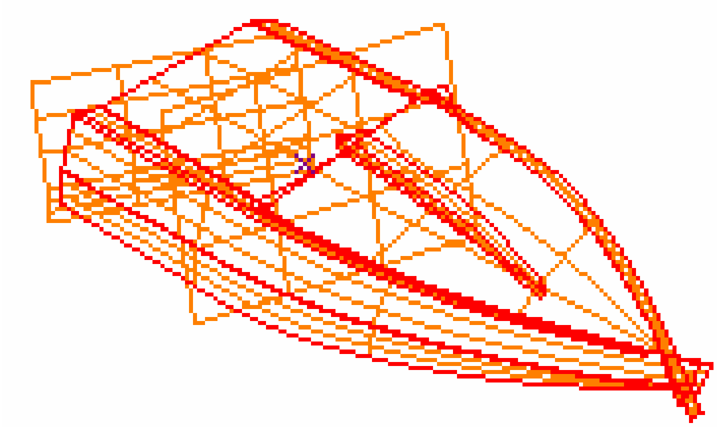

Figure 31: Wire diagram of hull

7.3.1. Inclining Tests

In order to gain a further understanding of a vessel's performance characteristics, it was necessary to determine a number of parameters for the vessel. Some of these values were relatively simple to determine. For example, the length and beam of the vessel are values that can be measured using simple tools in most environments. Some values, however, require more complicated tools and specific conditions to be accurately determined. One such set of values is known as hydrostatic data.

As the name implies, hydrostatic values are measured while the vessel is stationary. For these experiments, the vessel was placed in the ballast tank. During this process, properties such as list and trim, the waterline length, and draft were determined. The focus of this experimental session, however, was to determine the location of the center of gravity of the vessel as outfitted. This was performed via a conventional inclining test, which indirectly first determines the vertical distance from the metacenter of the vessel (a point about which the vessel rotates) to its center of gravity. This parameter is abbreviated as GM_T and is called the transverse metacentric height. The subscript "T"—which is used to differentiate the transverse value from the longitudinal value—is often dropped. In stability analysis, the transverse case is the most vital to determine a vessel's overall stability since vessels are typically much more stable in the longitudinal direction. Efforts are therefore concentrated on behavior in the transverse direction and behavior because that is the most critical direction. It is also an important factor in calculating most of the hydrodynamic coefficients.

In order to determine GM, an inclining test was conducted. The vessel was loaded as it would be in running condition and placed in the tank. An inclinometer was placed on the deck to measure the angle that the vessel rotated. A weight was placed on the deck to cause the vessel to list, or heel transversely to one side when the weights were shifted off the vessel's centerline. Initially, both weights were centered so that the vessel did not list. Then, the weight was slowly moved towards the side of the vessel in small increments. The position of the weight was recorded along with the angle of inclination. After the weight reached one side of the vessel, the process was repeated for the other side. The data from this experiment were plotted (Figure 32) and the linear relationship was observed.

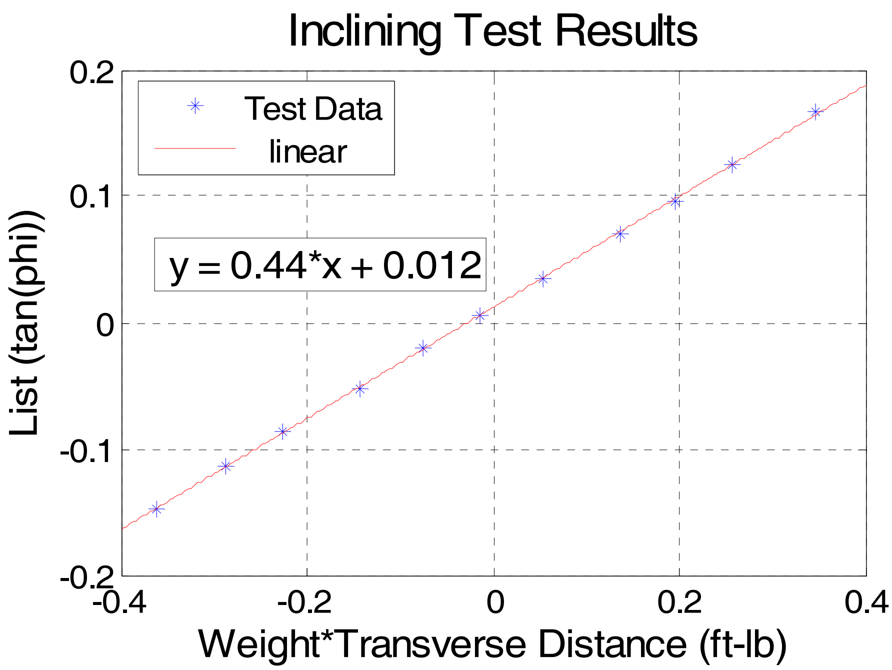

Figure 32: Results from inclining tests

One of the significant considerations when making this plot was to ensure that the proper sign convention was followed. For the transverse distance, values towards starboard were positive while values towards port were negative. The same was true of the inclined angles so that the resulting plot took on a linear characteristic. The values on the plot are related in such a way that the inverse of the slope of the line is equal to the displacement of the vessel (in lbs) multiplied by GM. Since the displacement was known, GM could be determined:

$$\begin{aligned} &slope = 0.44 \;{}^{1}\!/_{ft \cdot lb} \\ &{}^{1}\!/_{slope} = 2.273\, ft \cdot lb \\ &GM_T = {}^{2.273\, ft \cdot lb}\!/_{\Delta} = {}^{2.273\, ft \cdot lb}\!/_{10.04 lb} \\ &GM_T = 0.2264\, ft \end{aligned} \tag{17}$$

These results are valid for when the vessel is in the exact condition in which it was inclined, specifically including added mass of the weight and the inclinometer. However, the

results from this experiment were necessary for a complete understanding of the vessel's hydrostatic characteristics because they would be combined from the results of the next portion of the experimentation in order to achieve the full set of hydrostatic values. The values obtained "as inclined" can be corrected mathematically to represent the vessel's condition without the additional items onboard.

7.3.2. Data Analysis Software

There are a number of important characteristics of vessels that can be determined based on an accurate model of the hull shape. Previously documented efforts had produced such a model for this research. The model was in a form that could be electronically input to a software program called Fastship which is for designing and analyzing marine hullforms. The software was used to calculate basic hydrostatic information for a series of trim angles using both the running displacement and the inclined displacement. The software is not able to calculate the value for GM, so the previous experimentation was useful. The contribution of the software data was that it was now possible to convert the GM that was experimentally determined under increased displacement conditions to that of regular running conditions through a series of calculations. Using hydrostatic data from the even keel reports, the conversion was achieved.

The vertical distance from the keel to the metacenter (KM) is the sum of the position from the keel to the vertical center of buoyancy (VCB) and the distance from the center of buoyancy to the metacenter (BM_T). It is also equal to the draft (T) and the distance from the waterline to the metacenter (M_T):

$$\begin{aligned} KM &= VCB + BM_T = 0.148 + 0.412 = 0.560\,ft \\ KM &= T + M_T = 0.186 + 0.356 = 0.542\,ft \\ KM &\approx 0.55\,ft \end{aligned} \tag{18}$$

Since these values were not exactly the same, an average was taken as an estimate for KM. Now that KM and GM are known, the distance from the keel to the center of gravity (KG) can be calculated:

$$KG_{(asInc)} = KM - GM = 0.55 - 0.2264 \approx 0.32\,ft \tag{19}$$

At this point, a transition was made from the inclined condition to the running condition by accounting for the effects of the added weights on the vessel.

$$\left(KG_{new}\right)\left(\Delta_{new}\right) = \left(KG_{asInc}\right)\left(\Delta_{asInc}\right) - kg_1 w_1 - kg_2 w_2 \tag{20}$$

Assuming the weight and the inclinometer are homogeneous, the kg value is simply the vertical distance from the keel to the center of the object. Those measurements were taken, and the new KG was determined:

$$\begin{aligned} &\left(KG_{new}\right)\left(7.85lb\right) = \left(0.32\right)\left(10.04\right) - \left(0.3854\right)\left(1.45\right) - \left(0.5146\right)\left(0.74\right) \\ &KG_{new} = 0.2896\,ft \end{aligned} \tag{21}$$

The ultimate objective of these calculations is to determine GM for the vessel in running condition. In actuality, there are two GM values for a vessel, transverse and longitudinal. Since this is the case, it was necessary to determine both the transverse and longitudinal KM for the vessel from the hydrostatic data in the Fastship report. Using the same process as previously described, the KM values were determined:

$$\begin{aligned} KM_T &\approx 0.62\,ft \\ KM_L &\approx 5.72\,ft \end{aligned} \tag{22}$$

At this point, it was possible to finally determine the GM values of interest.

$$\begin{aligned}
GM_T &= KM_T - KG \\
GM_T &= 0.62 - 0.2896 \\
GM_T &\approx 0.33\,ft \\
GM_L &= KM_L - KG \\
GM_L &= 5.72 - 0.2896 \\
GM_L &\approx 5.43\,ft
\end{aligned} \tag{23}$$

These values are significant for a few reasons. Primarily, the GM value of a vessel is a way to gain an understanding about the vessel's stability. A higher GM value means that a vessel will be more stable. This is understood by noticing the difference in the transverse and longitudinal values of this particular vessel. As expected, the longitudinal GM is significantly greater than the transverse GM. This means that the vessel is more likely to roll than it is to pitch, which is intuitive based on the relative difference between the length and the width of the vessel. These values were also useful because software is available which uses these relative stability measurements, along with a few other hydrostatic measurements, to accurately estimate the coefficients for a mathematical model of the vessel. The results from this estimation process will be valuable as future controllers become more complex.

The hydrostatic testing produced useful results. The inclining test showed a strong linear correlation between the angle of inclination and the position of the inclining weight, which indicates a successful measurement. The data from the Fastship program allowed for a greater understanding of the vessel parameters in order to help determine the maneuvering characteristics of the vessel. It was now necessary to begin dynamic testing of the vessel to determine some important relationships between the different control settings.

7.3.3. 120 ft Tow Tank Tests

This vessel has two actuators that it depends on to achieve motion – the propeller and the rudder. An operator is able to control those actuators by sending desired signals to the remote-control receiver, which then relays those signals to either the shaft motor or to the servomotor which controls the rudder. With the Innovation First EDU-RC microprocessor acting as an intermediary between the operator and the motors, the specific value sent to each motor can be exactly controlled. On this premise, a series of experiments were run in order to determine the relationship between the different settings and the resulting performance of the vessel.

The first experiments were conducted in the 120 ft towing tank. This is a relatively narrow tank, but it is easily accessible and useful for straight runs. The objective of this series of experiments was to determine the relationship between the output signal from the microprocessor and the resulting speed of the vessel. These experiments were rudimentary yet effective. A set distance was marked on the tank and the time it took the vessel to traverse that distance was recorded. From this information, the average velocity over that course was calculated.

The primary difficulty that was encountered in this testing series was how to exactly control the output of the microprocessor without having to reprogram it for each speed change. Using the remote control alone was not enough because the output was too sensitive to control to the level of single output values, and repeatability was an issue. In order to overcome these problems, software had to be written that essentially turned the remote control throttle mechanism into an incrementing device.

The neutral output from the microprocessor to the speed controller for the drive motor was 127. Under normal conditions, a slight displacement of the throttle mechanism on the remote control could increase that output up to 140, which was impractical for this research

(resulting in high speed). The software modification that was conducted on the microprocessor made it so that a full deflection of the throttle joystick was defined to only increase the microprocessor output a single increment, from 127 to 128. To increase again, the joystick had to be returned to the neutral position and then fully deflected. Decreasing the output value was accomplished by deflecting the joystick in the reverse direction. In this way, the specific output of the microprocessor could be known and controlled.

These tests were successful in determining a reference point for the relationship between the throttle setting and speed. For the throttle settings tested, the data behaved in a roughly quadratic pattern (Figure 33). However, observations revealed that, at the higher throttle settings, the vessel was on the verge of making a significant transition into some sort of planing or semi-planing mode and would have dramatically increased speed. For the requirements of this research, however, displacement mode was desired. Another observation that was made over the entire course of this experimentation process was that the throttle output did not depend on the throttle setting alone. Factors such as the charge of the batteries, particularly those powering the EDU-RC since the motor battery voltage was relatively constant, and the amount of lubrication on the propeller shaft drastically affected the output of the motor. Therefore, while this data shows the relative performance of the throttle output, the exact location of this curve on the throttle setting spectrum varied significantly.

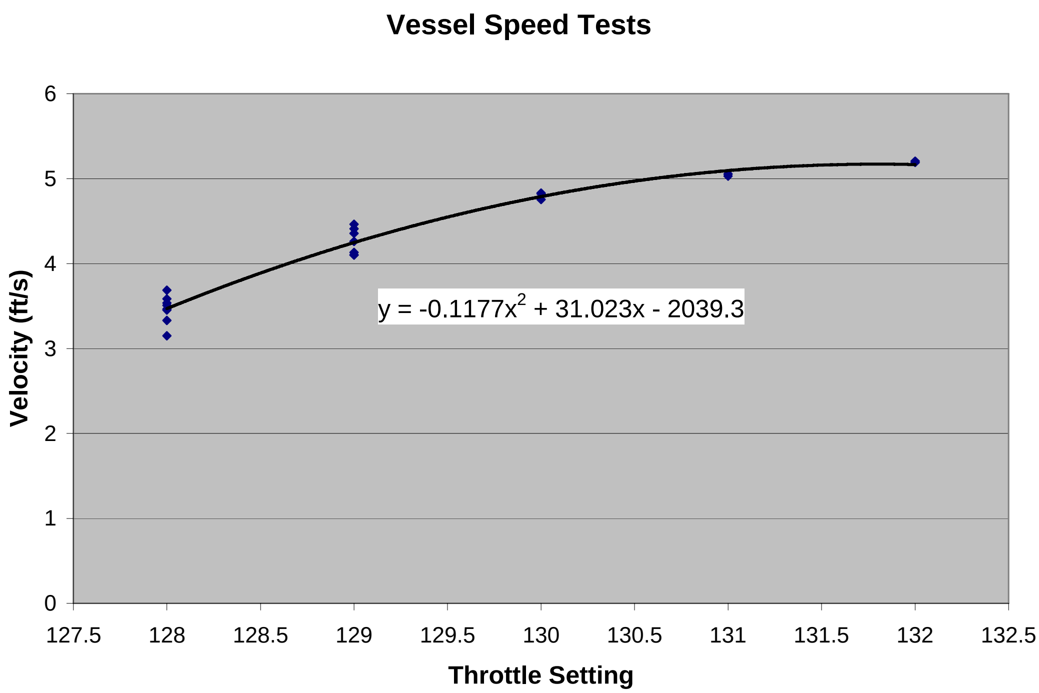

Figure 33: Results of throttle setting tests

7.3.4. 380 ft Tank Tests

The final portion of the vessel testing was conducted in the 380 ft towing tank. This tank is significantly wider than the 120 ft tank, so maneuvering experiments were possible. The goal of these experiments was to identify the relationship between the rudder position and the turning characteristics of the vessel. The tests that were run for this portion of the research were experimental in their own right because of the reliance on video data to determine the necessary performance measurements.

The primary maneuver that was used for this series of tests was a simple circle. The rudder was controlled in the same way the throttle had been controlled in the previous tests, although instead of a single increment for each joystick deflection, the output value was increased or decreased by a value of twenty. This was because there was little noticeable

difference between single rudder increments in addition to the fact that there was still relatively restricted mobility and the turns had to be made quickly.

A few observations were quickly made about the vessel's performance before any quantitative data was gathered. When no rudder was commanded, the vessel had a tendency to drift to starboard. This phenomenon could be compensated for by adjusting the neutral setting of the rudder. However, there was still a marked difference in the vessel's ability to make right and left turns. The right turns were much tighter than the left turns were. Although this probably has something to do with the arrangement of the hardware, as the rudder is offset to the starboard side of the vessel, it is also affected by the vertical location and rotation of the propeller. The propeller is designed to be a surface-piercing propeller. Even though it does not come completely out of the water at lower speeds, it does breach the surface. This means that there is more area pushing water at the bottom of the stroke than at the top, and the direction of rotation would cause the propeller to push the stern of the vessel to port, which would reduce the right turning radius and affect the straight-line tracking of the vessel.

With this in mind, the maneuvering tests were conducted. While a video camera recorded the runs, circles were driven using different rudder angles and throttle settings. Due to the disparity in turning performance, the vessel was only able to make a complete left circle at a setting of 27, one increment away from the maximum left rudder output of 7. A couple of left turns were successfully documented. Since the right turns were tighter, complete circles were possible for the 3rd, 4th, 5th, and 6th increments to the right. These experiments were run multiple times with differing throttle settings. The primary throttle setting was 129, since that setting was slow enough to allow multiple rudder settings to complete turns but it was fast enough to be useful in actual application.

In order to evaluate the data, it was necessary to determine a method to measure the actual value of the turning diameter and to associate that with the rudder output setting. By overlaying captured still shots from the recorded video on each other, the position of the vessel at each side of the circle was determined (Figure 34). The location of the edge of the tank directly in line with the diameter between those two positions was also marked. This way, the absolute measurement of the diameter could be determined based on knowledge of the actual width of the tank and the diameter of the vessel in the photos relative to the width of the tank in the photos. The percentage of the actual tank the vessel traversed during the maneuver was measured so the actual value of the turning diameter could then be calculated.

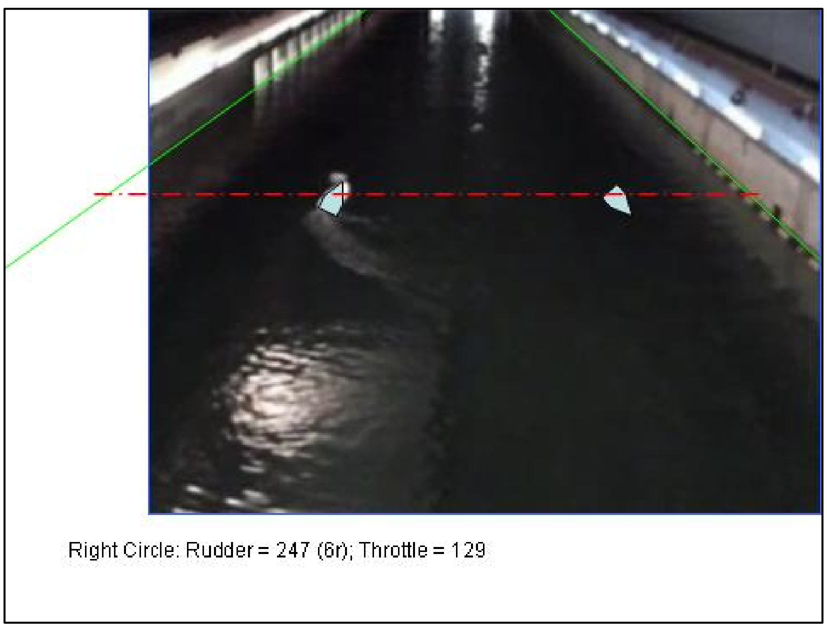

Figure 34: Example of turning radius measurement process

7.4. Yaw Rate Model

Another contribution of the video data was the amount of time it took to complete each circle. With this information, not only could the turning radius be determined, but the turning rate could also be calculated. This information was useful because the strategy for modeling the

system had shifted from a complex model involving the transient dynamics to a simpler model made possible by the observed quick response time of the vessel. This meant that a relationship between the rudder setting and the yaw rate would be sufficient to serve as the model for developing the autonomous controller.

Using the data from the video files, this relationship was calculated. When the turning rate for each rudder setting was determined, these values plotted against each other and a regression was made through the data (Figure 35). These particular data points were all measured at the primary throttle setting of 129, and experimentation showed that this model would be sufficient for other throttle settings around that operating point. The output of this regression became the actual model of the system used by the autonomous controller. This model shows that based on certain rudder displacements, specific turning rates can be expected. This is the same information provided by the complex dynamic models, although they account for transient factors that are present in large ships as a result of their increased mass and consequent momentum that are not significant factors in this design.

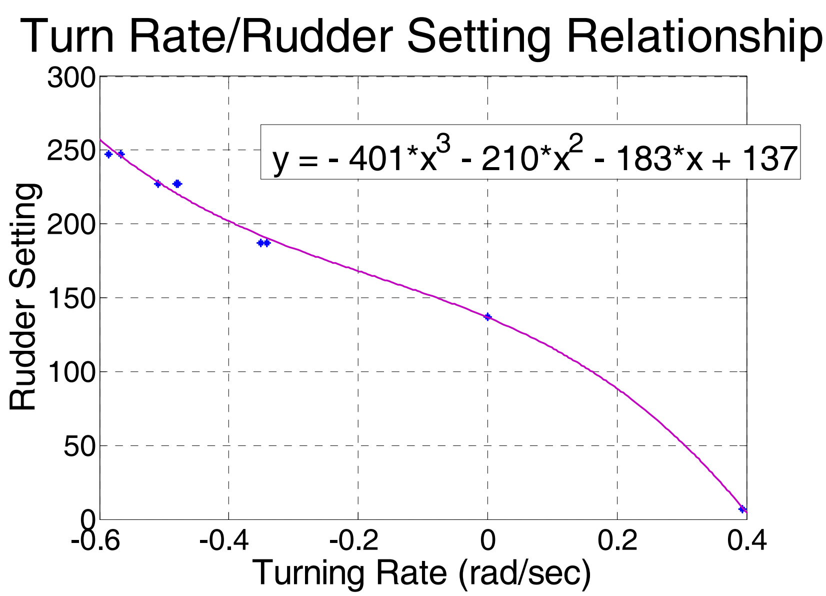

Figure 35: Mathematical relationship between yaw rate and rudder setting

7.5. Modeling Conclusions

The modeling process went through a series of stages until it reached completion. Initially, background investigations were made to understand some of the modeling techniques that were currently available. Initial measurements of the hull were performed to derive some of the parameters for use in these models. These hull measurements enabled the calculation of the hydrostatic data using a computer program. Experiments were then conducted in controlled environments (quiescent tanks) to determine the remainder of the necessary information. One of the significant results of these experiments was the observation that the vessel responded quickly to actuator inputs, so a complex model was not necessary for moderate-speed operation in displacement mode. This model would drastically reduce the amount of computation power required by the controller and increase the functionality of the data gathering processes. A basic model was developed from the free-running tests which proved effective in the final operation of the vessel.

8. Controller Design

Each phase of this design process has been critical, but these phases were designed to support the control system that was necessary to guide the vessel autonomously. A controller is designed to use information provided by various sensors and knowledge about the system it is to control to determine the necessary outputs of that system in order to achieve the desired results. Control systems are used in many situations, from the obvious robotic applications to economic systems highly affected by an adjustable interest rate, and they all function under this same basic premise. In this research, the system that was controlled was the vessel and accompanying maneuvering hardware. Different sensors were actuated with varying levels of success and relied upon accordingly. Using this information, a controller was designed that effectively guided the vessel to the desired destination in the waters surrounding the U.S. Naval Academy.

8.1. Theory

There were a number of considerations that were made when planning the operating theory of this controller. It was important to remember that the intent of this research was to design a controller that would be effective for moderate-speed travel. Also significant was the observation that the vessel quickly responded to inputs from the control surfaces, which means that there were no observable transient characteristics in the vessel's maneuverability. Since the GPS receiver was the most reliable sensor, the plan was to use the GPS data as the primary input for the navigational controller. The course, speed, and position information would be an excellent foundation for autonomous guidance. The microprocessor would calculate the necessary course to each waypoint and the vessel would follow that course to the final destination.

8.2. Plant Characteristic Estimation

There are many ways to mathematically model a vessel's maneuvering characteristics, and some are much more accurate than others. Over the course of this research, however, it was realized that there can be no substitute for actually observing the vessel maneuver. The data gathered from these observations lead to an accurate representation of the system. Despite the investigations into the different modeling techniques that have been developed and the efforts that were made to populate those models with valid coefficients, the representation of the system ultimately used by the controller was derived from observed maneuvers made by the vessel. This representation was particularly useful because it was possible to directly implement to the software onboard the Rabbit microprocessor. Although it neglected many of the precise characteristics represented by the high order models, these characteristics were not significant in the moderate-speed, highly-responsive system used for this research.

The turning radius tests made in the 380 ft towing tank were particularly useful for this derivation. The desired information from these tests was the turning rate, or angular velocity, for each rudder setting value. The video data analysis provided the turning diameter, but the most important piece of information was the amount of time it took to complete each turn. With that information, it was possible to calculate the angular velocity for each rudder setting.

Once these angular velocities were calculated and tabulated, a representation for the system was derived. It was important to remember that the overall objective of this process was to enable the microprocessor to automatically choose a rudder setting to achieve the necessary turning rate to quickly come onto the desired course to the next waypoint. This was the motivation for the characterization of the yaw rate model that was developed from the 380 ft towing tank data. That model proved effective for guiding the vessel in the proper direction.

8.3. Control Implementation

With the yaw-rate model, it was possible to transfer the control algorithm into the Rabbit software. There were many steps to this process. To begin, the data from the GPS receiver had to be refined so that it was useful for the control algorithm. Then the microprocessor had to determine the necessary course to reach the desired waypoint. At this point, a gain controller was used to determine the desired yaw rate based on the difference between the desired heading and the actual heading. Once the desired yaw rate was determined, it was input to the rudder setting polynomial derived from the video data and the appropriate rudder setting was sent to the actuator microprocessor.

The GPS receiver provided the microprocessor with useful navigational information, but this information had to be further manipulated so that it was meaningful for the microprocessor. The distance to the next waypoint and the track that the vessel must take to get to it were important pieces of information that could not be provided by the GPS receiver alone. Calculating the distance between two coordinates seemed initially to be a standard geometry problem. The differences between the latitudinal and longitudinal coordinates of those two points were treated as the sides of a right triangle, and the length of the hypotenuse was straight-line distance between the points. However, the units of those differences were either degrees of latitude or degrees of longitude, which are not necessarily equal. Therefore it was necessary to first convert those differences into feet before the length of the hypotenuse could be calculated. In the Annapolis area, one degree of longitude is 284207 feet, and one degree of latitude is 364224 feet. With this information, the distance between the current and desired position was calculated.

This distance information was necessary to determine exactly when a waypoint was reached. In theory, the controller for this system would guarantee that the vessel would come within its turning radius of the desired waypoint because, in the worst case scenario, it would reach that distance and then circle the waypoint continuously. In control terminology, this is called *uniform ultimate boundedness* [*25*]. Given this characteristic, a condition was set such that when the vessel came within the left turn radius of a waypoint (since that was the largest possible turn radius) the controller began to seek the next waypoint.

The next step was to calculate the course that was necessary to reach the waypoint. Although calculating an angle from one point to another based on a fixed coordinate system is also a standard geometry problem, it is complicated by the fact that one equation may produce the correct solution in the one quadrant, but separate considerations had to be made for the characteristics of other quadrants as well as the specific considerations for the four cardinal directions. Therefore, specific cases had to be established with different equations for each condition to ensure that the correct course was derived. In essence, it was necessary to compute the four-quadrant arctangent. Since a different equation would be necessary in each of the four quadrants, four cases were established in the software. The first test was whether the waypoint was to the east or west of the position. If the longitude of the waypoint was less than the longitude of the position, the waypoint was to the east of the vessel and in one of the two right quadrants since the current position of the vessel was considered the origin. If the first condition were true, the latitude was measured. If the latitude of the waypoint was greater than that of the position, the course was be found by:

$$\psi = \tan^{-1}\left(\frac{\Delta lon}{\Delta lat}\right) \tag{24}$$

This equation also accounted for the course 000° because the longitude value was in the numerator. If the waypoint was instead in the bottom-right quadrant, a 90° correction was necessary so that the equation became:

$$\psi = 90° + \tan^{-1}\left(\frac{\Delta lat}{\Delta lon}\right) \tag{25}$$

This condition accounted for the course 090° since the latitude difference was in the numerator.

If the waypoint was instead to the west of the position, the same two conditions for latitude were investigated. In the case that the waypoint was to the north of the position, the course to that waypoint was calculated as:

$$\psi = 270° + \tan^{-1}\left(\frac{\Delta lat}{\Delta lon}\right) \tag{26}$$

This calculation allowed for a course of 270°. The final possibility was that the waypoint was below the position. For this condition, the last equation was:

$$\psi = 180° + \tan^{-1}\left(\frac{\Delta lon}{\Delta lat}\right) \tag{27}$$

If it was necessary for the vessel to travel on course 180°, this condition would calculate that course. All of these conditions were necessary to properly calculate the course from the vessel's current position to the desired waypoint. They were coded into the NavBoard software and proved to be functional in determining the necessary course during autonomous navigation.

With the desired heading known, it was possible to develop the actual controller for the system. A basic controller was chosen for this application because it would be easy to tune and any problems would be relatively simple to locate and correct. This control process was particularly intuitive. The difference between the desired heading and the actual heading was calculated. This difference was multiplied by a constant value, known as a gain, to determine the

desired yaw rate of the vessel. If the difference was large, the desired yaw rate would be large because a significant variation in heading would be necessary. Conversely, if the difference was relatively small, only minor rudder corrections would be necessary so the desired yaw rate would be low. Adjusting the gain allowed the actual relationship between the heading error and desired yaw rate to be tuned so that the proper balance was achieved between a system that overcompensated for minor adjustments and one that required a large amount of time to get on track.

The actual control equation used in the software was:

$$\dot{\psi} = k \cdot \Delta\psi \tag{28}$$

In this equation, $\dot{\psi}$ is the desired yaw rate, *k* is the controller gain, and $\Delta\psi$ is the desired change in heading. The result of this equation, the desired yaw rate, is the input to the yaw rate model that was derived from the experimental data. Figure 36 illustrates the general control process, where a desired heading is compared with the actual heading, the result is multiplied by a constant gain, that value is conditioned by the plant model, and the result is an output to the actuators.

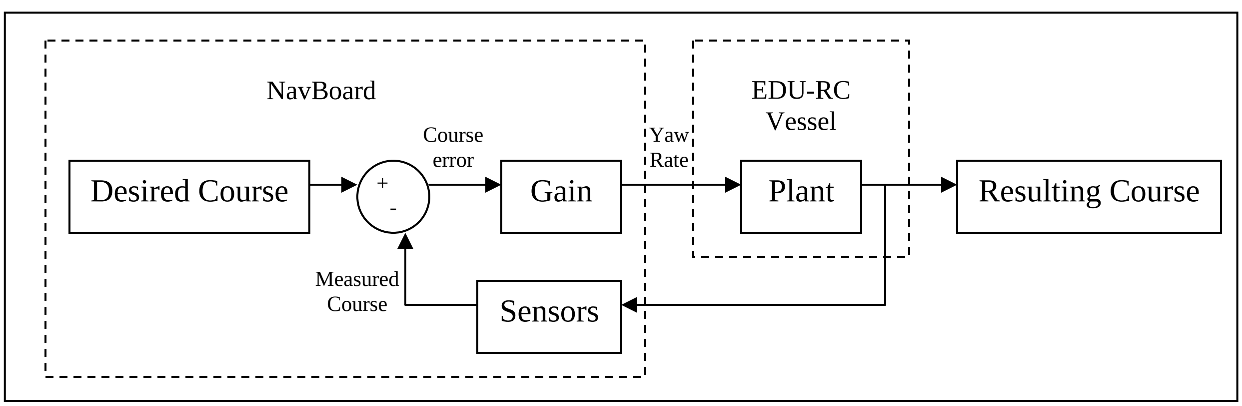

Figure 36: Block diagram of control system

Generally, the actual heading was output by the GPS receiver. The inaccuracy of the magnetometer was significant enough that this value would not be useful as the sole source of directional information. However, the magnetometer did serve one significant purpose. In the event that the GPS data was temporarily unavailable, which could be caused by a physical obstruction to the signal, the controller used the instantaneous magnetometer value as the desired course to follow until GPS data became available again. Although the exact value of the magnetometer output was not accurate geographically, it was stable and smooth. Following that track was an acceptable form of temporary navigation as long as the vessel had been traveling on course for a period of time before the GPS signal was lost.

The output of this controller was a desired yaw rate, which was then input to the polynomial equation that had already been derived. This equation output a rudder setting which could then be sent to the actuator microprocessor and then sent to the rudder servomotor. However, there was one final step to take before the rudder setting could be sent. The servomotor operated on a range from roughly 1 to 255. If it received a command higher or lower than those values, it would loop to the other end of the spectrum and act accordingly. For example, a setting of 1 would result in a hard right rudder. If that setting were decreased to a negative value, however, the servomotor would act as if it had received 255, or a hard left rudder. This would adversely effect the vessel's maneuvering ability. For this reason, hard limits were established for the rudder command output so that if the desired value was less than 1 or more than 255, it was restrained to that maximum effective value. This meant that most large angle corrections would be accomplished with the same rudder setting, but this was necessary in order to properly handle the servomotor parameters. This conditioned value was then sent to the EDU-RC and the rudder behaved accordingly.

Section 1.02

8.4. Testing

This controller was tested a number of times before the final operational test of the system was conducted. The first tests were conducted on the relative safety of land, and when the results were acceptable, the vessel was released into the water for a series of evaluations. The initial tests were conducted using a preset series of waypoints so that the performance could be easily observed and the location of the vessel could be controlled.

8.4.1. Land Tests

The vessel was first tested on land so that if there was a significant deficiency in the control algorithm it could be realized and corrected before the vessel was lost at sea. The first step of this process was to map out a suitable area for testing. Using the GPS receiver for this process seemed like a logical solution since that would be the sensor that would be providing the actual data to the controller. A few waypoints were measured and input to the NavBoard code before the tests began. To test the controller, the vessel was carried out to the test area and walked along the course. Directional corrections were made according to the position of the rudder so that a rough estimation of the actual performance of the vessel could be made. These tests were successful in proving the general concept of the control system (Figure 37).

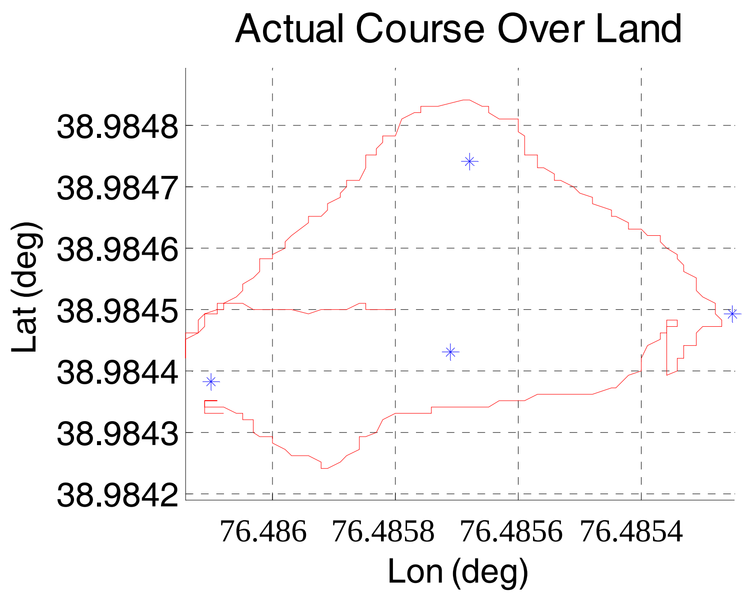

Figure 37: Course achieved by following vessel's rudder position

8.4.2. Water Tests

Based on the success of the land-based testing, water tests were conducted in College Creek and the Severn River, near the grounds of the U. S. Naval Academy. The mapping process for the test area was more complicated because specific waypoints could not be easily measured. Instead, the perimeter of the test area was measured and plotted and appropriate waypoints were chosen which were within that test area. These waypoints were hard coded into the NavBoard software and the vessel was set out on the water. The code was set up so that the vessel would continue to loop through the waypoints multiple times so that the performance could be sufficiently evaluated, and the results were successful. The vessel made two complete cycles between the waypoints with no incidents when the test was deemed complete. Also, information was gained about the data gathering process which allowed the sentence structure that was sent to the wireless modem to be refined so that it contained more useful information. In particular, the sentence did not include enough decimal values in the GPS coordinates to be

able to differentiate them from one another since the tests were conducted in a relatively small area. These corrections were made so that the final evaluations would include useful GPS data that could be used for verifying the performance of the system.

Based on the results of these two tests, it was determined that the controller is effective. The vessel was able to navigate autonomously to desired locations, which was the primary objective of this research. However, the water-borne testing had been fairly limited, so a final large scale test was conducted. To begin this process, waypoints were determined using ACD. These waypoints were used by the controller as guidance through the course. Figure 38 shows the actual course of the vessel next to the waypoints generated by the ACD process. The connection with the data stream was lost towards the end of the run, so a theoretical track was added to the figure at the '+' symbol. During the test run, wind was a significant factor. This caused the vessel to deviate from the track, especially at farther distances from the waypoints. As the vessel approached each waypoint, it corrected for the deviations caused by the wind, as illustrated in Figure 38, which shows the vessel's path through part of the Severn River and down College Creek.

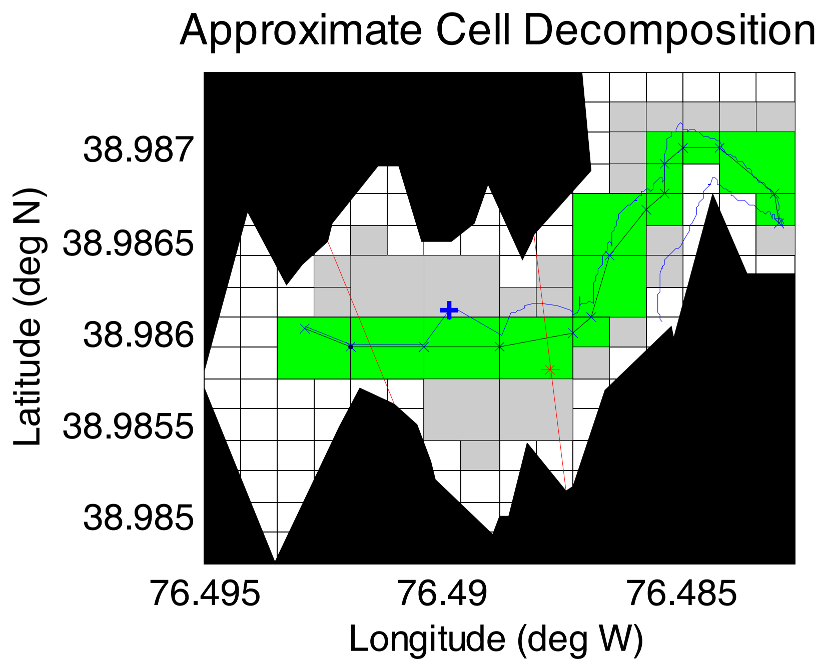

Figure 38: Plot of ACD with actual course overlaid

The vessel was deployed into the river and driven manually until it had a clear line to the first waypoint, which was a significant distance into the Severn River. This was the first time the vessel had encountered a significant sea state, and some observations were made about its performance. At low speeds, it was capable of traveling into the sea effectively. However, once it reached the first waypoint and attempted to change directions, the adverse conditions had a greater effect. The lateral displacement caused by the waves made it difficult for the GPS system to effectively determine the vessel's track. This caused the controller to guide the vessel in multiple directions until the correct track was reached. Also, this track took the vessel through following seas. It was difficult to maintain constant progress as a result of the waves. However, the vessel was able to continue reaching waypoints until it reached more sheltered waters in College Creek.

At this point, the journey became smoother. The controller responses were more accurate, with some deviation due to the fact that the gain had been calibrated during the initial

tests, which were conducted without the sensor pod to increase the safety and stability of the vessel. The fact that the same controller was able to guide the vessel in both conditions is testimony to the robustness of this design strategy. The vessel successfully navigated the creek, avoiding both bridges it had to pass under even though the range sensors were not effective for large-scale testing. If the range sensors had been functioning properly, the obstacle avoidance process would have modified the course slightly because of the proximity with which the vessel passed a bridge support, but the course tracking algorithm would have minimized any deviation from the desired course. The destination for the vessel had been set as the center pier at the Hubbard Hall. The vessel reached that pier and was successfully retrieved (Figure 39).

Figure 39: Vessel autonomously approaching retrieval point

The full course for this autonomous transition was roughly a half-mile. The vessel completed this course, coming within 9 ft of the exact point at which the endpoint was measured. This is a significant result. Despite the wind, waves, and current, as well as the satellite drift that was present that day, the vessel was able to maintain an appropriate track in order to successfully

navigate the course. The results of this test were incredibly encouraging as they proved the effectiveness of this autonomous surface vessel.

9. Final Conclusions

To date, there has been relatively little research and development in the field of sea surface autonomous vehicles as compared to aerial, ground, and underwater vehicles. This project therefore aimed to help contribute to the advance development of understanding in the field of autonomous sea surface vessels. This research was presented to both systems and marine engineering audiences, and its applicability was well received [26], [27].

The research culminated in an operational platform that was tested *in situ*. The procurement, assembly, and integration of the hardware for this system were the first steps in this project. This is a necessary process in any Systems Engineering design because of the multifaceted nature of the discipline. Achieving a smooth integration of the sensors with the processors and platform hardware was critical so that an autonomous design could be achieved. This process resulted in the development of the NavBoard, which has proved useful in multiple design applications. In addition, the software and electronics required to facilitate communication between the sensors and microprocessors were key contributions to this research. Once the hardware was selected and tested, the project was ready for the completion of the hardware design and the beginning of earnest efforts toward designing and testing the controller.

Research was also conducted into a variety of different modeling techniques that could be used to develop the controller for the vessel. A number of models were selected for close investigation based on appealing characteristics of each, and the final decision was to be based on experimental results with the different models. It was expected that some would perform better than others, and the model with the best performance would be used for the final control design. In the end, however, a simple mathematical equation derived from video data of free

running maneuvering tests served to model the dynamics of the vessel in such a way that a control algorithm was successfully designed and implemented.

A significant experimentation process was conducted before this equation was derived. Basic measurements were taken and a three-dimensional representation of the vessel was rendered. This representation served as the basis for deriving a number of static values of the vessel. Experiments were also conducted on the water to gain a greater understanding of the vessel's dynamic properties. These experiments proved valuable in determining the vessel's rapid response characteristics and ultimately the relationship between the yaw rate and the rudder setting. Data from these experiments was also valuable for beginning to populate the hydrodynamic coefficient matrices for some of the complex models.

The completion of this process allowed for the design of the autonomous control system. A theoretical design was implemented into the Rabbit software and tested in various conditions. A final test was conducted based on a course that was chosen by the path planning system. The vessel autonomously traveled from its initial position in the Severn River to its destination up College Creek. The success of this test was critical for this research. As a result, it is clear that the navigational system is effective for directing the vessel as required. Each of the pieces of the project was successful in producing a final product which met the ultimate objective of this research – autonomous navigation.

Future research with this vessel could accomplish a number of objectives. Signal processing refinements for the NavBoard could lead to the development of *in situ* state identification and advanced control systems. Refinements to the range sensors would allow for deployed testing of the obstacle avoidance algorithm. Finally, hardware modifications could allow for increased endurance for large scale testing and increased applicability. However, the

results achieved over the course of this study are valuable. The problems investigated and solved as a result of this research serve as significant contributions to the Systems Engineering and Naval Architecture/Ocean Engineering fields. This project presented many challenges, but the end result of a functional autonomous surface vessel is a great success.

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Appendix A. Navigation Board Operating Software

```
//Rabbit 3000 Navigation Board v1.0
//J Bradshaw 06-02-2005
//C Reed     10-12-2005
/* PB0 is the serial B clock line(SCLK)
   PC4 is the data output(MOSI)
   PC5 is the data input(MISO)

   PB5 is MicroMag3 (Compass) SSNOT (!CS) Line (Output from Rabbit)
   PB6 is MicroMag3 (Compass) DRDY Line (Low after reset, High after command and data is ready)
   PB7 is MicroMag3 (Compass) RESET Line (Output from Rabbit) Usually Low, Toggled from L-H-L to
reset

   PG0 is MCP3008 Analog to digital converter CS Line (Output from Rabbit)

   PC0 is TXD, Rabbit Transmit and MAXSTREAM Modem Receive
   PC1 is RXD, Rabbit Receive and MAXSTREAM Modem Transmit

   PC2 is TXE, Rabbit Transmit and GPS Receive
   PC3 is RXE, Rabbit Receive and GPS Transmit

   ---------MCP3008 A2D Channels------------
   Channel 0 - External Input
   Channel 1 - External Input
   Channel 2 - Roll Gyro Temp
   Channel 3 - Roll Gyro Output
   Channel 4 - Pitch Gyro Output
   Channel 5 - Accelerometer Y Output  //Really X but changed due to orientation
   Channel 6 - Accelerometer X Output  //Really Y but changed due to orientation
   Channel 7 - Accelerometer Z Output
*/
#define BOUTBUFSIZE 127
#define BINBUFSIZE 127
#define COUTBUFSIZE 127
#define CINBUFSIZE 127
#define DOUTBUFSIZE 127
#define DINBUFSIZE 127

#define EOUTBUFSIZE 127
#define EINBUFSIZE 127

#define SPI_SER_B             //Choose serial port B for SPI bus
#define SPI_CLK_DIVISOR 5     //Minimal clock divisor
#use "spi.lib"                //Contains the SPI functions

#define mag_deviation 0.0     //-10.5 Maryland  //Magnetic deviation in degrees

//Range sensor
#use "i2c.lib"             //Contains i2c_init();
#use "i2c_devices.lib"     //Contains I2CWrite(), and I2CRead() Functions.
#define SON_ADDRESS 0xe0   //SONAR SRF08 DEFAULT ADDRESS
#define SON_ADDR_RGT 0xe2
#define SON_ADDR_CNT 0xe4
#define SON_ADDR_LFT 0xe6

//-------GLOBAL VARIABLES---------------------------------------------
unsigned int A2D_value[8]; //A2D result on channel 0 -7
float X_offset, Y_offset, Z_offset, Pitch_offset, Roll_offset;
float accel_Xvolts, accel_Yvolts, accel_Zvolts, Pitch_volts, Roll_volts;
float Xg[2], Yg[2], Zg[2];
float XMg, YMg, ZMg; // Calculated acceleration measurements (weighted sums)
float angX, angY, angZ;
float Pitch, Roll, Temp;   //ADXRS150 rate gyro output
float Roll_deg, Pitch_deg;
int MMx,MMy,MMz;  //Compass component readings
float heading;    //Calculated compass heading
int i, j, k, m;         //Used in for loop for index (array address)
float time, time_diff, time2, time_diff2;
```

```
// GPS Variables
   char buf_temp[20];
   char sentence[200];
   int GPSsample, sig_lost;
   char lat_sent[11], lon_sent[12];
   float lat, lon;
   float samp_array[1024];
   float mean, std_dev;
   char sentDrec[100];
   char sampnumsent[10];
   char SOG[10], TMG[10];
   float knots, mph, track;
   char cmd;
   int LED_flag;
   const char factory_reset[6] = {0x10, 0x1E, 0x46, 0x10, 0x03};
   const char req_pos[5] = {0x10, 0x24, 0x10, 0x03};
   const char save_mem_set[5] = {0x10, 0x8E, 0x10, 0x03};

// Control Variables
   char ans, ans2;
   char s[10];
   int val, wpt;
   float des_head, head_error, des_yaw, rud_set;
   float wpt_lon[20], wpt_lat[20];
   float d_lon, d_lon_ft, d_lat, d_lat_ft;
   float yaw_gain, dist;
   float lat1, lat1min, lon1, lon1min, lat2, lon2;

//--------------Prototypes---------------------------------------------
xmem nodebug void MsDelay(int MS);
xmem speed float calc_mean(float *float_array, int num_pts);
xmem speed float calc_standard_deviation(float *float_array, float mean, int num_pts);
xmem unsigned int Get_MCP3008_A2D(int chan);
xmem unsigned int Get_Extern_SPI(int CS, int chan);   // Added 17 Feb
xmem void InitMicroMag3(void);
xmem int ReadMicroMag3(char);
xmem nodebug void ftoa_PIC(float x, char *str, int prec);
xmem void find_offset(void);
xmem void Init_NavBoard(void);
void RMC_Parse(char *sentence);

xmem nodebug void MsDelay(int MS)   // Millisecond delay
   {
    long SavTimer, TimerDiff;
    TimerDiff = 0;
    SavTimer = MS_TIMER;
    while(TimerDiff < MS) {TimerDiff = MS_TIMER - SavTimer;}
   }

// Calculates mean of a set of values
xmem speed float calc_mean(float *float_array, int num_pts)
{
   int i;
   float mean;

   mean = 0;
   for(i=0;i<num_pts;i++)
   {
      mean += float_array[i];
   }
   mean /= num_pts;

   return mean;
}

// Calculates standard deviation of a set of values
xmem speed float calc_standard_deviation(float *float_array, float mean, int num_pts)
{
```

```
   int i;
   float standard_dev, variance;

   variance = 0;
   for(i=0;i<num_pts;i++)
      variance += pow((float_array[i] - mean), 2);//***Overflows possible floating pt exponent
   variance = (variance/(num_pts - 1));
   standard_dev = sqrt(variance);

   return standard_dev;
}

// Queries A2D converter for data
xmem nodebug unsigned int Get_MCP3008_A2D(int chan)
{
   unsigned char ch_result[3];
   unsigned int A2D_result;
   char cword[3];

   cword[0] = 0x01;
   cword[1] = (chan << 4) + 0x80;   //0x80 is single ended input

   BitWrPortI(PGDR,&PGDRShadow,0,0);   //Take CS/SHDN Pin LOW to Start Conversion

   SPIWrRd(&cword, &ch_result, 3); //3 byte transfer to and from A2D

   BitWrPortI(PGDR,&PGDRShadow,1,0);   //Take CS/SHDN Pin High to End Conversion
   ch_result[1] &= 0x03;
   A2D_result = (ch_result[1] * 256) + ch_result[2];
   return A2D_result;
}

// Reads from SPI bus
xmem unsigned int Get_Extern_SPI(int CS,int chan)
{
   unsigned char ch_result[3];
   unsigned int A2D_result;
   char cword[3];

   cword[0] = 0x01;
   cword[1] = (chan << 4) + 0x80;   //0x80 is single ended input

   if(CS==2)                              //Take CS/SHDN Pin LOW to Start Conversion
      BitWrPortI(PBDR,&PBDRShadow,0,3);
   else if(CS==3)
      BitWrPortI(PBDR,&PBDRShadow,0,4);
   else
      BitWrPortI(PBDR,&PBDRShadow,0,2);

   SPIWrRd(&cword, &ch_result, 3); //3 byte transfer to and from A2D

   if(CS==2)                              //Take CS/SHDN Pin HIGH to End Conversion
      BitWrPortI(PBDR,&PBDRShadow,1,3);
   else if(CS==3)
      BitWrPortI(PBDR,&PBDRShadow,1,4);
   else
      BitWrPortI(PBDR,&PBDRShadow,1,2);

   ch_result[1] &= 0x03;
   A2D_result = (ch_result[1] * 256) + ch_result[2];
   return A2D_result;
}

// Initializes magnetometer
xmem void InitMicroMag3(void)
{
   BitWrPortI(PBDR,&PBDRShadow,1,5);      //Start with PB5 (SSNOT of MicroMag3) High
   BitWrPortI(PBDDR, &PBDDRShadow, 1, 5); //Make PB5 an OUTPUT for SSNOT Pin
```

```
   BitWrPortI(PBDR,&PBDRShadow,0,7);      //Start with PB7 (RESET of MicroMag3) LOW
   BitWrPortI(PBDDR, &PBDDRShadow, 1, 7); //Make PB7 an OUTPUT for RESET Pin

   BitWrPortI(PBDDR, &PBDDRShadow, 0, 6); //Make PB6 an INPUT for DRDY Pin
}

// Reads magnetometer
xmem nodebug int ReadMicroMag3(char axis)
{
   int i;
   int measurment;
   char result[2];
   char Xmeas[1], Ymeas[1], Zmeas[1];

   Xmeas[0] = 0x61;
   Ymeas[0] = 0x62;
   Zmeas[0] = 0x63;

   result[0] = 0;
   result[1] = 0;
   BitWrPortI(PBDR,&PBDRShadow,0,5);   //Take SSNOT Pin LOW

   BitWrPortI(PBDR,&PBDRShadow,0,7);      //Take PB7 (RESET of MicroMag3) LOW
   BitWrPortI(PBDR,&PBDRShadow,1,7);      //Take PB7 (RESET of MicroMag3) HIGH
   for(i=0;i<3;i++); //short delay
   BitWrPortI(PBDR,&PBDRShadow,0,7);      //Take PB7 (RESET of MicroMag3) LOW again

   if((axis == 'Y') || (axis == 'y'))
   {
      SPIWrite(Ymeas, 1); //1 byte transfer to MicroMag3
   }
   else
   {
      if((axis == 'Z') || (axis == 'z'))
      {
         SPIWrite(Zmeas, 1); //1 byte transfer to MicroMag3
      }
      else
         //if((axis == 'X') || (axis == 'x'))   //default axis
      {
         SPIWrite(Xmeas, 1); //1 byte transfer to MicroMag3
      }
   }

   while(BitRdPortI(PBDR, 6) == 0);    //wait for DRDY to go HIGH
   SPIRead(result, 2); //1 byte transfer from MicroMag3
   BitWrPortI(PBDR,&PBDRShadow,1,5);   //Take SSNOT Pin HIGH

// result /= 32;
   measurment = (result[0] * 256) + result[1];
   return measurment;
}

// Converts float value to ASCII
xmem nodebug void ftoa_PIC(float x, char *str, int prec)
{
   int ie, i, k, ndig;

   ndig = (prec<=0) ? 7: (prec > 22 ? 23: prec+1);
   ie = 0;

   //If x is negative, write a minus and reverse
   if(x<0)
   {
      *str++ = '-';
      x = -x;
   }
   //Put x in range of 1 <= x < 10
   if(x > 0.0)
```

```
      while(x < 1.0)
      {
         x *= 10.0;
         ie--;
      }
   while(x>= 10.0)
   {
      x = x/10.0;
      ie++;
   }
   if(ie<0)
   {
      *str++ = '0';
      *str++ = '.';
      if(ndig < 0)
         ie = ie - ndig; //limit zeros if underflow
      for(i=-1;i > ie; i--)
         *str++ = '0';
   }
   for(i=0;i<ndig;i++)
   {
      k = (int)x;
      *str++ = k + '0';
      if(i==ie)
         *str++ = '.';
      x-= k;
      x*=10;
   }
   *str = '\0';
}

// Determines initial sensor offset
xmem void find_offset(void)
{
   int i, j;

   Temp = Get_MCP3008_A2D(2); //Read the Roll Gyros Temp Output
   Roll_offset = Get_MCP3008_A2D(3);    //Read the analog value for the Roll Rate Gyro (ADXRS150)
   Pitch_offset = Get_MCP3008_A2D(4);    //Read the analog value for the Pitch Rate Gyro
(ADXRS150)
   X_offset = Get_MCP3008_A2D(6);      //Read the analog value for the X axis (MMA7260Q)
   Y_offset = Get_MCP3008_A2D(5);      //Read the analog value for the Y axis
   Z_offset = Get_MCP3008_A2D(7);      //Read the analog value for the Z axis

   for(i=0;i<100;i++)      //take 100 averages
   {
      Temp += Get_MCP3008_A2D(2);            //Read Temperature for Roll Gyro
      Temp /= 2.0;
      Roll_offset += Get_MCP3008_A2D(3);    //Read the analog value for the Roll Rate Gyro
(ADXRS150)
      Roll_offset /= 2.0;
      Pitch_offset += Get_MCP3008_A2D(4);    //Read the analog value for the Pitch Rate Gyro
(ADXRS150)
      Pitch_offset /= 2.0;
      X_offset += Get_MCP3008_A2D(6);      //Read the analog value for the X axis
      X_offset /= 2.0;
      Y_offset += Get_MCP3008_A2D(5);      //Read the analog value for the Y axis
      Y_offset /= 2.0;
      Z_offset += Get_MCP3008_A2D(7);      //Read the analog value for the Z axis
      Z_offset /= 2.0;
   }
   Temp *= .0048875855;
   Roll_offset *= .0048875855; // 5.0v / 1023
   Pitch_offset *= .0048875855;

   X_offset *= .0048875855;
   Y_offset *= .0048875855;
   Z_offset *= .0048875855;
// X_offset = 1.65;
```

```
// Y_offset = 1.65;
   Z_offset -= 0.800;

// printf("Xoff= %5.3f Yoff= %5.3f Zoff= %5.3f\n", X_offset, Y_offset, Z_offset);
}

// Initializes NavBoard
xmem void Init_NavBoard(void)
{

      LED_flag = 0;
      MsDelay (2200);      //Minimum 2.1 second delay before commands can be received

      //Serial Port E, Lassen GPS
      serEopen(9600);
      serEparity(PARAM_OPARITY);

      //TSIP Protocall
      serEputc(0x10);
      serEputc(0xBC); //Protocall configuration command word
      serEputc(0xff); //Current port
      serEputc(0x06); //4800 Input baud rate
      serEputc(0x06); //4800 output baud rate
      serEputc(0x03); //8 bits (Number data bits)
      serEputc(0x00); //parity bits
      serEputc(0x00); //1 stop bit
      serEputc(0x00); //no flow control
      serEputc(0x02); //TSIP input on
      serEputc(0x04); //TSIP output off, NMEA output on
      serEputc(0x00); //reserved
      serEputc(0x10);
      serEputc(0x03);

      serEclose;
      MsDelay(100);
      serEopen(4800);
      serEparity(PARAM_NOPARITY);

      MsDelay(100);

      serEputc(0x10);
      serEputc(0x7A);
      serEputc(0x00); //subcode
      serEputc(0x01); //interval in seconds
      serEputc(0x00); //reserved
      serEputc(0x00); //reserved
      serEputc(0x01); //Byte 4 (bit 0 = RMC, 1 = on)
      serEputc(0x00); //Byte 5 (bit 0 = GGA, 1 = on)
      serEputc(0x10);
      serEputc(0x03);

      MsDelay(100);

      serEputc(0x10);
      serEputc(0x8E);
      serEputc(0x10);
      serEputc(0x03);

      //Serial Port D if RF Modem
      serDopen(9600);
      serDparity(PARAM_NOPARITY);

      MsDelay (1000);
      //receive and parse GPS data

      // Serial Port F (TTL)
      serFopen(19200);
      serFparity(PARAM_NOPARITY);
```

```
   SPIinit();

   BitWrPortI(PBDDR, &PBDDRShadow, 1, 2); //Make PB2 an OUTPUT for External SPI CS
   BitWrPortI(PBDDR, &PBDDRShadow, 1, 3); //Make PB3 an OUTPUT for External SPI CS
   BitWrPortI(PBDDR, &PBDDRShadow, 1, 4); //Make PB4 an OUTPUT for External SPI CS // Last 3
lines added

//CS Line for MPC3008 A2D converter PG0
   BitWrPortI(PGDR,&PGDRShadow,1,0);      //Start with PG0 (CS of MCP3008) High
   BitWrPortI(PGFR, &PGFRShadow, 0, 0);   //Make PG0 Function as Normal I/O
   BitWrPortI(PGDDR, &PGDDRShadow, 1, 0); //Make PG0 an OUTPUT for CS Pin

   //SEL1 Line for MMA7260Q Accelerometer
   BitWrPortI(PGDR,&PGDRShadow,0,5);      //Start with PG5 SEL1 Low  1.5g scale
   BitWrPortI(PGFR, &PGFRShadow, 0, 5);   //Make PG5 Function as Normal I/O
   BitWrPortI(PGDDR, &PGDDRShadow, 1, 5); //Make PG5 an OUTPUT for CS Pin

   //SEL2 Line for
   BitWrPortI(PGDR,&PGDRShadow,0,4);      //Start with PG4 Low  1.5g scale
   BitWrPortI(PGFR, &PGFRShadow, 0, 4);   //Make PG0 Function as Normal I/O
   BitWrPortI(PGDDR, &PGDDRShadow, 1, 4); //Make PG0 an OUTPUT for CS Pin

   //SLEEP Line for XSTREAM MODEM
   BitWrPortI(PGDR,&PGDRShadow,0,1);      //Start with PG1 Low
   BitWrPortI(PGFR, &PGFRShadow, 0, 1);   //Make PG1 Function as Normal I/O
   BitWrPortI(PGDDR, &PGDDRShadow, 1, 1); //Make PG4 an OUTPUT for SLEEP Pin // Last 4 lines
added

   //ON/Status Light (LED) PF2
   BitWrPortI(PFDR,&PFDRShadow,1,2);      //Start with PF2 (LED) High - OFF
   BitWrPortI(PFFR, &PFFRShadow, 0, 2);   //Make PF2 Function as Normal I/O
   BitWrPortI(PFDDR, &PFDDRShadow, 1, 2); //Make PF2 an OUTPUT for LED

   //RESET of RF Modem PF3
   BitWrPortI(PFDR,&PFDRShadow,1,3);      //Start with PF3 High
   BitWrPortI(PFFR, &PFFRShadow, 0, 3);   //Make PF3 Function as Normal I/O
   BitWrPortI(PFDDR, &PFDDRShadow, 1, 3); //Make PF3 an OUTPUT for RESET Signal
   BitWrPortI(PFDR,&PFDRShadow,0,3);      //Take Reset LOW
   for(i=0;i<10;i++);
   BitWrPortI(PFDR,&PFDRShadow,1,3);      //Take Reset HIGH

   InitMicroMag3();  //Initialize the MicroMag3 Compass
}

// Reads and parses GPS data
void RMC_Parse(char *sentence)
{
   for(j=0;j<10;j++)  //clear strings
            {
               SOG[j] = '\0';
               TMG[j] = '\0';
               sampnumsent[j] = '\0';
            }
            for(j=0;j<11;j++)  //clear strings
            {
               lat_sent[j] = '\0';
            }
            for(j=0;j<12;j++)  //clear strings
            {
               lon_sent[j] = '\0';
            }

            itoa(GPSsample, sampnumsent);
            strcat(sampnumsent, "\0");

            for(i=0;sentence[i] != ',' ;i++);  //Goto first comma, UTC of Position Fix
            i++;
            for( ;sentence[i] != ',' ;i++);    //Goto second comma, Status (A = Valid, V =
navigation receiver warning)
```

```
i++;

if((sentence[i] != 'A') && (sentence[i] != 'V'))   //Invalid if not 'A' or 'V'
{
   LED_flag = 0;
   for(j=0;j<10;j++)  //clear strings
   {
      SOG[j] = '\0';
      TMG[j] = '\0';
   }
   for(j=0;j<11;j++)  //clear strings
   {
      lat_sent[j] = '\0';
   }
   for(j=0;j<12;j++)  //clear strings
   {
      lon_sent[j] = '\0';
   }
}
if(sentence[i] == 'A')  //Valid GPS Data
{
   LED_flag = 1;
}
if(sentence[i] == 'V')  //Invalid GPS Data
{
   LED_flag = 0;
   for(j=0;j<10;j++)  //clear strings
   {
      SOG[j] = '\0';
      TMG[j] = '\0';
   }
   for(j=0;j<11;j++)  //clear strings
   {
      lat_sent[j] = '\0';
   }
   for(j=0;j<12;j++)  //clear strings
   {
      lon_sent[j] = '\0';
   }
}

for( ;sentence[i] != ',' ;i++);        //Goto third comma, Latitude
i++;                                   //Goto beginning of Latitude Feild

if(sentence[i] != ',')
{
   for(j=0;sentence[i] != ',' ;i++,j++)         //Display Lat Data
   {
      lat_sent[j] = sentence[i];
   }
   lat_sent[j] = '\0';  //append a NULL
   lat = atof(lat_sent);
}
else
{
   strcpy(lat_sent, "NoData");
}

for( ;sentence[i] != ',' ;i++);        //Goto fourth comma, N or S
i++;

if((sentence[i] != ',')&&(lat_sent[0] != ' '))
{
   lat_sent[j] = sentence[i];
   lat_sent[j+1] = '\0';
}

for( ;sentence[i] != ',' ;i++);        //Goto fifth comma, longitude
i++;                                   //Goto beginning of Longitude Feild
```

```
            if((sentence[i] != ',') && (sentence[i] != 'V'))
            {
               for(j=0;sentence[i] != ',' ;i++,j++)         //Display Lon Data
               {
                  lon_sent[j] = sentence[i];
               }
               lon_sent[j] = '\0';  //append a NULL
               lon = atof(lon_sent);
            }
            else
            {
               strcpy(lon_sent, "NoData");
            }

            for( ;sentence[i] != ',' ;i++);        //Goto sixth comma, E or W
            i++;

            if((sentence[i] != ',')&&(lon_sent[0] != ' '))
            {
               lon_sent[j] = sentence[i];
               lon_sent[j+1] = '\0';
            }

            for( ;sentence[i] != ',' ;i++);        //Goto seventh comma, SOG in knots
            i++;

            if(sentence[i] != ',')
            {
               for(k=0; sentence[i] != ','; i++)
               {
                  SOG[k] = sentence[i];
                  k++;
               }

               k++;
               SOG[k] = '\0';

               knots = atof(SOG);
               mph = 1.150779 * knots;

               SOG[0] = '\0';
               ftoa_PIC(mph, SOG, 1);
            }

            for( ;sentence[i] != ',' ;i++);        //Goto eighth comma, track made good in deg
true
            i++;

            if(sentence[i] != ',')
            {
               for(k=0; sentence[i] != ','; i++)
               {
                  TMG[k] = sentence[i];
                  k++;
               }

               k++;
               TMG[k] = '\0';

               track = atof(TMG);
            }
} // RMC Parsing

//------------------------MAIN----------------------------------
void main()
{
   int samples;
   long act_samp;
```

```
   const char i2c_SRF08_meas_type[]  = {0x51};  //Ranging Mode, result in cm
   const char i2c_Max_gain[] = {0x00};          //Make maximum gain 94 (requires index of 0x01)
   const char i2c_Max_dis[] = {0x8C};           //Make maximum range 6m (requires index of 0x02)
   char i2c_data_in_SRF08[1];                   //Single character buffer to store bytes read
from SRF08
   unsigned int echo[5];                        //Echo results from SRF08

 // Initialize Variables
   yaw_gain = 0.5;
   time = 0.0;
   time2 = 0.0;
   time_diff = 0.0;
   time_diff2 = 0.0;
   Roll_deg = 0.0;
   Pitch_deg = 0.0;
   act_samp = 1;
   samples = 1;
   GPSsample = 1;
   sig_lost = 0;
   lat = 0;
   lon = 0;
   Xg[0] = 0.0;
   Xg[1] = 0.0;
   Yg[0] = 0.0;
   Yg[1] = 0.0;
   Zg[0] = 0.0;
   Zg[1] = 0.0;
   XMg = 0.0;
   YMg = 0.0;
   ZMg = 0.0;
   wpt = 0;

// Waypoints
   wpt_lon[0] = 76.482758;
   wpt_lat[0] = 38.986550;
   wpt_lon[1] = 76.482987;
   wpt_lat[1] = 38.986586;
   wpt_lon[2] = 76.482988;
   wpt_lat[2] = 38.986753;
   wpt_lon[3] = 76.484150;
   wpt_lat[3] = 38.987003;
   wpt_lon[4] = 76.484925;
   wpt_lat[4] = 38.987003;
   wpt_lon[5] = 76.485313;
   wpt_lat[5] = 38.986919;
   wpt_lon[6] = 76.485313;
   wpt_lat[6] = 38.986753;
   wpt_lon[7] = 76.485700;
   wpt_lat[7] = 38.986669;
   wpt_lon[8] = 76.486475;
   wpt_lat[8] = 38.986419;
   wpt_lon[9] = 76.486863;
   wpt_lat[9] = 38.986085;
   wpt_lon[10] = 76.487250;
   wpt_lat[10] = 38.986002;
   wpt_lon[11] = 76.488800;
   wpt_lat[11] = 38.985918;
   wpt_lon[12] = 76.490350;
   wpt_lat[12] = 38.985918;
   wpt_lon[13] = 76.491900;
   wpt_lat[13] = 38.985918;
   wpt_lon[14] = 76.492851;
   wpt_lat[14] = 38.986026;
   lat2 = wpt_lat[0];
   lon2 = wpt_lon[0];

   for(i=0;i<10;i++)    //Clear Sentences
   {
      lat_sent[i] = '\0';
```

```
      lon_sent[i] = '\0';
      sampnumsent[i] = '\0';
   }

   Init_NavBoard();  //Initialize the Navigation Board I/O and Hardware on the Rabbit
   i2c_init();                                    //Initialize ES308SBC I2C PORT, (PD6 = SCL,
PD7 = SDA)
                                                  // both are Open Drain

   serDputs("\r\n     NAV BOARD OPTERATIONAL  \r\n");
   serDputs("  Xg Yg Zg  Heading  Roll  Pitch   Sample-Num   \r\n");

   find_offset();    //Find offset of accelerometer

   while(1)
   {
   costate  //GPS sentence parsing
      {
         wfd cof_serEgets(sentence, 100, 2000);    //Get GPS String, wfd="wait for done",
cof_serEgets()-costate will only execute when true
                                                  //DOUBLE CHECK the value 100, possibly set it
to 150 to grab all 150 chars for sentence
         if((sentence[0] == '$') &&
            (sentence[1] == 'G') &&
            (sentence[2] == 'P') &&
            (sentence[3] == 'R') &&
            (sentence[4] == 'M') &&
            (sentence[5] == 'C'))
         {
            RMC_Parse(sentence);

            // Calculates track to next waypoint
            d_lon_ft = d_lon*284207.0;
            d_lat_ft = d_lat*364224.0;
            dist = sqrt(d_lon_ft*d_lon_ft + d_lat_ft*d_lat_ft);

         // Determines when vessel reaches waypoint
            if(dist < 13.0)
            {
               wpt++;
               lat2 = wpt_lat[wpt];
               lon2 = wpt_lon[wpt];
            }

         // Calculates positions in DD.XXXX format
            lon1 = floor(lon/100.0);
            lon1min = lon - lon1*100.0;
            lon1 = lon1 + lon1min/60.0;

            lat1 = floor(lat/100.0);
            lat1min = lat - lat1*100.0;
            lat1 = lat1 + lat1min/60.0;

         // Calculates distance from next waypoint
            d_lon = abs((lon2 - lon1)*10000);
            d_lon = d_lon/10000.0;
            d_lat = abs((lat2 - lat1)*10000);
            d_lat = d_lat/10000.0;

         // 4-Quadrant arctangent
            if((lon2 <= lon1) && (lon1 != 0.0))
            {
               if(lat2 > lat1)
               {
                  des_head = atan(d_lon/d_lat)*180.0/PI;
               }

               if((lat2 <= lat1) && (lon2 != lon1))
               {
```

```
                des_head = 90.0 + atan(d_lat/d_lon)*180.0/PI;
             }
          }

          if((lon2 >= lon1) && (lon1 != 0.0))
          {
             if((lat2 >= lat1) && (lon2 != lon1))
             {
                des_head = 270.0 + atan(d_lat/d_lon)*180.0/PI;
             }

             if(lat2 < lat1)
             {
                des_head = 180.0 + atan(d_lon/d_lat)*180.0/PI;
             }
          }

       // Indicates to take heading measurement from compass
          if((lat1 == 0.0) && (sig_lost == 0))
          {
             des_head = heading;
             sig_lost++;
          }

          if(lat1 == 0.0)
             {track = heading;}

          if((lat1 != 0.0) && (sig_lost != 0))
             {sig_lost = 0;}

       // Heading controller
          head_error = des_head - track;
          if(head_error < -180.0)
             {head_error += 360.0;}
          if(head_error >= 180.0)
             {head_error -= 360.0;}
          des_yaw = yaw_gain * head_error * PI / 180.0;
          if(des_yaw > 0.3944)
             {des_yaw = 0.3944;}
          if(des_yaw < -0.5764)
             {des_yaw = -0.5764;}

       // Yaw rate model
          rud_set = -(401.0*des_yaw*des_yaw*des_yaw)-(210.0*des_yaw*des_yaw)-
(183.0*des_yaw)+137.0;
          val = (int)rud_set;

          if(val > 255)
             {val = 255;}
          if(val < 1)
             {val = 1;}
          ans = (char)val;
          serFputs("r");
          serFputs(&ans);
          MsDelay(10);

          serErdFlush();

          GPSsample++;   //Increment the GPS Sample
       }
    }//costate

    costate
    {
       for(i=0;i<8;i++)                    //Sample A2D channels
       {
          A2D_value[i] = Get_MCP3008_A2D(i);
       }
       Roll_volts = (float)A2D_value[3] * .0048875855; //Convert to volts (5.0/1023)
```

```
        Pitch_volts = (float)A2D_value[4] * .0048875855;   //Convert to volts (5.0/1023)
        accel_Xvolts = (float)A2D_value[6] * .0048875855;
        accel_Yvolts = (float)A2D_value[5] * .0048875855;
        accel_Zvolts = (float)A2D_value[7] * .0048875855;

        // Rate Gyro Filtering
        Roll = (Roll_volts-Roll_offset)/.0125;    //12.5mV/deg/sec
        time_diff = (MS_TIMER-time)/1000.0;
        if((Roll > 0.9) || (Roll < -0.9))
        {Roll_deg = Roll_deg + (Roll*time_diff);}
        time = MS_TIMER;

        Pitch = (Pitch_volts-Pitch_offset)/.0125;    //12.5mV/deg/sec
        time_diff2 = (MS_TIMER-time2)/1000.0;
        if((Pitch > 0.9) || (Pitch < -0.9))
        {Pitch_deg = Pitch_deg + (Pitch*time_diff2);}
        time2 = MS_TIMER;

        Xg[0] = (accel_Xvolts-X_offset)/.800;     //800mV/g
        Xg[0] *= 100;
        XMg = ((((float)samples - 1.0)/(float)samples) * Xg[1]) + ((1.0/(float)samples) *
Xg[0]);
        Yg[0] = (accel_Yvolts-Y_offset)/.800;
        Yg[0] *= 100;
        YMg = ((((float)samples - 1.0)/(float)samples) * Yg[1]) + ((1.0/(float)samples) *
Yg[0]);
        Zg[0] = (accel_Zvolts-Z_offset)/.800;
        Zg[0] *= 100;
        ZMg = ((((float)samples - 1.0)/(float)samples) * Zg[1]) + ((1.0/(float)samples) *
Zg[0]);

         MMx = ReadMicroMag3('X');
         MMy = ReadMicroMag3('Y');
         MMz = ReadMicroMag3('Z');

      // Measure and calculate magnetometer heading
        heading = atan((float)MMy / (float)MMx);
        if((MMx < 0.0) && (MMy < 0.0))
           heading -= PI;
        if((MMx < 0.0) && (MMy >= 0.0))
           heading += PI;
        heading *= (180.0 / PI); //Change radians to degrees
        heading += mag_deviation;
        if(heading < 0.0)
           heading += 360.0;

        heading = 360.0 - heading;

      // Serial string
//      serDputs("$NAVDATA,");

        buf_temp[0] = '\0';              //heading
        ftoa_PIC(heading, buf_temp, 3);
        strcat(buf_temp, "\0");
        serDputs(buf_temp);
        serDputs(",");

        buf_temp[0] = '\0';              //Xg (Actually channel Y, but changed b/c of
orientation)
        ftoa_PIC(Xg[0], buf_temp, 3);
        strcat(buf_temp, "\0");
        serDputs(buf_temp);
        serDputs(",");

        buf_temp[0] = '\0';              //Yg
        ftoa_PIC(Yg[0], buf_temp, 3);
        strcat(buf_temp, "\0");
        serDputs(buf_temp);
        serDputs(",");
```

```
buf_temp[0] = '\0';              //Zg
ftoa_PIC(Zg[0], buf_temp, 3);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //Roll
ftoa_PIC(Roll_deg, buf_temp, 3);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //Pitch
ftoa_PIC(Pitch_deg, buf_temp, 3);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //lon1
ftoa_PIC(lon1, buf_temp, 7);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //lon2
ftoa_PIC(lon2, buf_temp, 7);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //lat1
ftoa_PIC(lat1, buf_temp, 7);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //lat2
ftoa_PIC(lat2, buf_temp, 7);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

serDputs(SOG);
serDputs(",");
serDputs(TMG);
serDputs(",");

buf_temp[0] = '\0';              //des_head
ftoa_PIC(des_head, buf_temp, 4);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //dist
ftoa_PIC(dist, buf_temp, 5);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

buf_temp[0] = '\0';              //rud_set
ftoa_PIC(rud_set, buf_temp, 3);
strcat(buf_temp, "\0");
serDputs(buf_temp);
serDputs(",");

serDputs("   \n\r");

Xg[1] = Xg[0];
```

```
         Yg[1] = Yg[0];
         Zg[1] = Zg[0];

         samples++;
      }//A2D costate

      costate
      {
         if(LED_flag == 0)
         {
            BitWrPortI(PFDR,&PFDRShadow,0,2);      //Turn ON LED
            waitfor(DelayMs(100));
            BitWrPortI(PFDR,&PFDRShadow,1,2);      //Turn Off LED
            waitfor(DelayMs(100));
            BitWrPortI(PFDR,&PFDRShadow,0,2);      //Turn ON LED
            waitfor(DelayMs(100));
            BitWrPortI(PFDR,&PFDRShadow,1,2);      //Turn Off LED
            waitfor(DelayMs(3200));
         }
         else
         {
            BitWrPortI(PFDR,&PFDRShadow,0,2);      //Turn ON LED
            waitfor(DelayMs(200));
            BitWrPortI(PFDR,&PFDRShadow,1,2);      //Turn Off LED
            waitfor(DelayMs(1000));
         }
      }//LED costate

/*    costate
      {
         I2CWrite(SON_ADDR_RGT, 0x00, i2c_SRF08_meas_type, 1);       //Takes measurement in
centimeters
         I2CWrite(SON_ADDR_RGT, 0x01, i2c_Max_gain, 1);              //Make max gain '100'
         I2CWrite(SON_ADDR_RGT, 0x02, i2c_Max_dis, 1);               //Make max range '11'm

         I2CWrite(SON_ADDR_CNT, 0x00, i2c_SRF08_meas_type, 1);       //Takes measurement in
centimeters
         I2CWrite(SON_ADDR_CNT, 0x01, i2c_Max_gain, 1);              //Make max gain '100'
         I2CWrite(SON_ADDR_CNT, 0x02, i2c_Max_dis, 1);               //Make max range '11'm

         I2CWrite(SON_ADDR_LFT, 0x00, i2c_SRF08_meas_type, 1);       //Takes measurement in
centimeters
         I2CWrite(SON_ADDR_LFT, 0x01, i2c_Max_gain, 1);              //Make max gain '100'
         I2CWrite(SON_ADDR_LFT, 0x02, i2c_Max_dis, 1);               //Make max range '11'm

         waitfor(DelayMs(65));      //Maximum wait period between trigger and read for 11 meters

         I2CRead(SON_ADDR_RGT, 0x03,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[0] = *i2c_data_in_SRF08;                    //Echo[0] is equal to low byte
         I2CRead(SON_ADDR_RGT, 0x02,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[0] += (*i2c_data_in_SRF08 <<= 8);           //Echo[0] equals Echo[0] plus High Byte

         I2CRead(SON_ADDR_CNT, 0x03,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[1] = *i2c_data_in_SRF08;
         I2CRead(SON_ADDR_CNT, 0x02,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[1] += (*i2c_data_in_SRF08 <<= 8);

         I2CRead(SON_ADDR_LFT, 0x03,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[2] = *i2c_data_in_SRF08;
         I2CRead(SON_ADDR_LFT, 0x02,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[2] += (*i2c_data_in_SRF08 <<= 8);

         I2CRead(SON_ADDR_RGT, 0x09,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[3] = *i2c_data_in_SRF08;
         I2CRead(SON_ADDR_RGT, 0x08,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[3] += (*i2c_data_in_SRF08 <<= 8);

         I2CRead(SON_ADDR_RGT, 0x11,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[4] = *i2c_data_in_SRF08;
```

```
         I2CRead(SON_ADDR_RGT, 0x10,i2c_data_in_SRF08,1);   //Reads byte from SON_ADDRESS (0xe0)
         echo[4] += (*i2c_data_in_SRF08 <<= 8);
      }*/   //Range sensor costate
   }//while(1)
}//main()
```

Appendix B. EDU-RC Operating Software

```
/*******************************************************************************
* FILE NAME: user_routines.c <EDU VERSION>
*
* DESCRIPTION:
*  This file contains the default mappings of inputs
*  (like switches, joysticks, and buttons) to outputs on the EDU RC.
*
*******************************************************************************/
#include <usart.h>

#include "ifi_aliases.h"
#include "ifi_default.h"
#include "ifi_utilities.h"
#include "user_routines.h"
#include "printf_lib.h"
#include "sensors.h"
#include "delays.h"

SensorPackType Sensors;


/*** DEFINE USER VARIABLES AND INITIALIZE THEM HERE ***/
/* EXAMPLES: (see MPLAB C18 User's Guide, p.9 for all types)
unsigned char wheel_revolutions = 0; (can vary from 0 to 255)
unsigned int  delay_count = 7;       (can vary from 0 to 65,535)
int           angle_deviation = 142; (can vary from -32,768 to 32,767)
unsigned long very_big_counter = 0;  (can vary from 0 to 4,294,967,295)
*/


/*******************************************************************************
* FUNCTION NAME: Limit_Switch_Max
* PURPOSE:       Sets a PWM value to neutral (127) if it exceeds 127 and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to be limited
* RETURNS:       void
*******************************************************************************/
void Limit_Switch_Max(unsigned char switch_state, unsigned char *input_value)
{
  if (switch_state == CLOSED)
  {
    if(*input_value > 127)
      *input_value = 127;
  }
}


/*******************************************************************************
* FUNCTION NAME: Limit_Switch_Min
* PURPOSE:       Sets a PWM value to neutral (127) if it's less than 127 and the
*                limit switch is on.
* CALLED FROM:   this file
* ARGUMENTS:
*     Argument       Type             IO   Description
*     --------       -------------    --   -----------
*     switch_state   unsigned char    I    limit switch state
*     *input_value   pointer           O   points to PWM byte value to be limited
* RETURNS:       void
*******************************************************************************/
void Limit_Switch_Min(unsigned char switch_state, unsigned char *input_value)
{
  if (switch_state == CLOSED)
```

```
  {
    if(*input_value < 127)
      *input_value = 127;
  }
}


/*******************************************************************************
* FUNCTION NAME: Limit_Mix
* PURPOSE:       Limits the mixed value for one joystick drive.
* CALLED FROM:   Default_Routine, this file
* ARGUMENTS:
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     intermediate_value    int    I
* RETURNS:       unsigned char
*******************************************************************************/
unsigned char Limit_Mix (int intermediate_value)
{
  static int limited_value;

  if (intermediate_value < 2000)
  {
    limited_value = 2000;
  }
  else if (intermediate_value > 2254)
  {
    limited_value = 2254;
  }
  else
  {
    limited_value = intermediate_value;
  }
  return (unsigned char) (limited_value - 2000);
}


/*******************************************************************************
* FUNCTION NAME: Setup_Who_Controls_Pwms
* PURPOSE:       Each parameter specifies what processor will control the pwm.
*
* CALLED FROM:   User_Initialization
*     Argument             Type    IO   Description
*     --------             ----    --   -----------
*     pwmSpec1              int     I   USER/MASTER (defined in ifi_aliases.h)
*     pwmSpec2              int     I   USER/MASTER
*     pwmSpec3              int     I   USER/MASTER
*     pwmSpec4              int     I   USER/MASTER
*     pwmSpec5              int     I   USER/MASTER
*     pwmSpec6              int     I   USER/MASTER
*     pwmSpec7              int     I   USER/MASTER
*     pwmSpec8              int     I   USER/MASTER
* RETURNS:       void
*******************************************************************************/
static void Setup_Who_Controls_Pwms(int pwmSpec1,int pwmSpec2,int pwmSpec3,int pwmSpec4,
                                    int pwmSpec5,int pwmSpec6,int pwmSpec7,int pwmSpec8)
{
  txdata.pwm_mask = 0xFF;         /* Default to master controlling all PWMs. */
  if (pwmSpec1 == USER)           /* If User controls PWM1 then clear bit0. */
    txdata.pwm_mask &= 0xFE;      /* same as txdata.pwm_mask = txdata.pwm_mask & 0xFE; */
  if (pwmSpec2 == USER)           /* If User controls PWM2 then clear bit1. */
    txdata.pwm_mask &= 0xFD;
  if (pwmSpec3 == USER)           /* If User controls PWM3 then clear bit2. */
    txdata.pwm_mask &= 0xFB;
  if (pwmSpec4 == USER)           /* If User controls PWM4 then clear bit3. */
    txdata.pwm_mask &= 0xF7;
  if (pwmSpec5 == USER)           /* If User controls PWM5 then clear bit4. */
    txdata.pwm_mask &= 0xEF;
  if (pwmSpec6 == USER)           /* If User controls PWM6 then clear bit5. */
```

```
    txdata.pwm_mask &= 0xDF;
  if (pwmSpec7 == USER)           /* If User controls PWM7 then clear bit6. */
    txdata.pwm_mask &= 0xBF;
  if (pwmSpec8 == USER)           /* If User controls PWM8 then clear bit7. */
    txdata.pwm_mask &= 0x7F;
}

void Initialize_TTL_Comms (void)
{
  Open2USART(USART_TX_INT_OFF &
    USART_RX_INT_OFF &
    USART_ASYNCH_MODE &
    USART_EIGHT_BIT &
    USART_CONT_RX &
    USART_BRGH_HIGH,
    128);

   Delay1KTCYx( 50 ); /* Settling time */
}


/*******************************************************************************
* FUNCTION NAME: User_Initialization
* PURPOSE:       This routine is called first (and only once) in the Main function.
*                You may modify and add to this function.
*                The primary purpose is to set up the DIGITAL IN/OUT - ANALOG IN
*                pins as analog inputs, digital inputs, and digital outputs.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
*******************************************************************************/
void User_Initialization (void)
{
  unsigned char dataRead;
  rom const char *strptr = "IFI TTL Tester ...";

/* FIRST: Set up the pins you want to use as analog INPUTs. */
  IO1 = IO2 = INPUT;        /* Used for analog inputs. */
    /*
     Note: IO1 = IO2 = IO3 = IO4 = INPUT;
           is the same as the following:

           IO1 = INPUT;
           IO2 = INPUT;
           IO3 = INPUT;
           IO4 = INPUT;
    */

/* SECOND: Configure the number of analog channels. */
  Set_Number_of_Analog_Channels(TWO_ANALOG);     /* See ifi_aliases.h */

/* THIRD: Set up any extra digital inputs. */
  /* The six INTERRUPTS are already digital inputs. */
  /* If you need more then set them up here. */
  /* IOxx = IOyy = INPUT; */
  IO6 = IO8 = IO10 = INPUT;      /* Used for limit switch inputs. */
  IO12 = IO14 = IO16 = INPUT;    /* Used for limit switch inputs. */

/* FOURTH: Set up the pins you want to use as digital OUTPUTs. */
  IO3 = IO4 = OUTPUT;
  IO5 = IO7 = IO9 = OUTPUT;     /* For connecting to adjacent limit switches. */
  IO11 = IO13 = IO15 = OUTPUT;  /* For connecting to adjacent limit switches. */

/* FIFTH: Initialize the values on the digital outputs. */
  rc_dig_out03 = rc_dig_out04 = 0;
  rc_dig_out05 = rc_dig_out07 = rc_dig_out09 = 0;
  rc_dig_out11 = rc_dig_out13 = rc_dig_out15 = 0;

/* SIXTH: Set your initial PWM values.  Neutral is 127. */
```

```
  pwm01 = pwm02 = pwm03 = pwm04 = pwm05 = pwm06 = pwm07 = pwm08 = 127;

/* SEVENTH: Choose which processor will control which PWM outputs. */
  Setup_Who_Controls_Pwms(MASTER,MASTER,MASTER,MASTER,MASTER,MASTER,MASTER,MASTER);

/* EIGHTH: Set your PWM output type.  Only applies if USER controls PWM 1, 2, 3, or 4. */
  /*   Choose from these parameters for PWM 1-4 respectively:                          */
  /*     IFI_PWM  - Standard IFI PWM output generated with Generate_Pwms(...)          */
  /*     USER_CCP - User can use PWM pin as digital I/O or CCP pin.                    */
  Setup_PWM_Output_Type(IFI_PWM,IFI_PWM,IFI_PWM,IFI_PWM);

  /*
     Example: The following would generate a 40KHz PWM with a 50% duty cycle
              on the CCP2 pin (PWM OUT 1):
          CCP2CON = 0x3C;
          PR2 = 0xF9;
          CCPR2L = 0x7F;
          T2CON = 0;
          T2CONbits.TMR2ON = 1;
          Setup_PWM_Output_Type(USER_CCP,IFI_PWM,IFI_PWM,IFI_PWM);
  */

/* Add any other user initialization code here. */

//  Initialize_Serial_Comms();
  Initialize_TTL_Comms();
//  Init_Serial_Port_Two();
//  Init_Serial_Port_Two();
//  stdout_serial_port = SERIAL_PORT_ONE;
//  printf("Please work!");

  Putdata(&txdata);             /* DO NOT CHANGE! */

  printf("%s\n", strptr);       /* Optional - Print initialization message. */

  dataRead = RCREG2;            //Dummy read to clear buffer
  dataRead = RCREG2;

  User_Proc_Is_Ready();         /* DO NOT CHANGE! - last line of User_Initialization */
}



/*******************************************************************************
* FUNCTION NAME: Process_Data_From_Master_uP
* PURPOSE:       Executes every 17ms when it gets new data from the master
*                microprocessor.
* CALLED FROM:   main.c
* ARGUMENTS:     none
* RETURNS:       void
*******************************************************************************/
void Process_Data_From_Master_uP(void)
{
   static unsigned char Toggle,dataRead,delay,dataOut;
   int i = 0;
   static int j = 0;
   static unsigned char sent[6];
   static unsigned char rud_cont, thr_cont, pod_cont;
   static int switchval = 0;
   static int pwmval = 127;
   static int thr_old;

   Getdata(&rxdata);   /* Get fresh data from the master microprocessor. */

//  Default_Routine();  /* Optional.  See below. */

   if (PWM_in5 > 200)
   {
      if (DataRdy2USART())
```

```
   {
         // Grab the next charcter from the USART and place it in the data structure
      sent[j] = getc2USART();

      if (sent[j] == 114)
      {
         printf("Rudder command received\n");
         if (DataRdy2USART())
         {
            rud_cont = getc2USART();
            printf("Rudder command is %d\n", (int)rud_cont);
            pwm01 = (int)rud_cont;
         }  //DataRdy2USART()
      }  // sent[j] == 114

      else if (sent[j] == 116)
      {
         printf("Throttle command received\n");
         if (DataRdy2USART())
         {
            thr_cont = getc2USART();
            printf("Throttle command is %d\n", (int)thr_cont);
            thr_old = pwm03;
            if(((thr_old - (int)thr_cont) <= 5) && ((thr_old - (int)thr_cont) >= -5))
            {
               //pwm03 = (int)thr_cont;
            }
         }  //DataRdy2USART()
      }  // sent[j] == 116

      else if (sent[j] == 112)
      {
         printf("Pod command received\n");
         if (DataRdy2USART())
         {
            pod_cont = getc2USART();
            printf("Pod command is %d\n", (int)pod_cont);
            pwm03 = (int)pod_cont;
         }  //DataRdy2USART()
      }  // sent[j] = 112

      j = j + 1;
   }  //DataRdy2USART()
   else
   {
   // If it failed then clear any possible errors
      RCSTA2bits.CREN = 0; // Disable the receiver
      RCSTA2bits.CREN = 1; // Re-enable the receiver
   }  // else

   if ((PWM_in3 < 75)&&(switchval > -1))
   {
      pwmval = pwmval - 1;
      switchval = -1;
   }
   if ((PWM_in3 > 200)&&(switchval < 1))
   {
      pwmval = pwmval + 1;
      switchval = 1;
   }
   if ((PWM_in3 < 200)&&(PWM_in3 > 75))
      {switchval = 0;}

   pwm03 = pwmval;
}  // PWM_in5 > 200

else
{
   pwm01 = -PWM_in1;
```

```
      pwm03 = PWM_in3;
   }  // else

   //RCSTA2bits.CREN = 0; // Disable the receiver
   /* if (j == 6)
   {
      printf("String = %d %d %d %d %d %d\r",
(int)sent[0],(int)sent[1],(int)sent[2],(int)sent[3],(int)sent[4],(int)sent[5]);
      j = 0;
   }*/

   Putdata(&txdata);             /* DO NOT CHANGE! */
}


/*******************************************************************************
* FUNCTION NAME: Default_Routine
* PURPOSE:       Performs the default mappings of inputs to outputs for the
*                Robot Controller.
* CALLED FROM:   this file, Process_Data_From_Master_uP routine
* ARGUMENTS:     none
* RETURNS:       void
*******************************************************************************/
void Default_Routine(void)
{
static int throttle = 1270;
static int th_d = 1270;
float range = 40.0;
float scale = 20.0;
static int i = 0;
static int j = 5;

if (PWM_in5 > 200)
{
// pwm03 = 127 + 127*j/100;
// printf("Output is %d percent\n",j);
   pwm03 = 132;
// printf("Output is %d\n",pwm03);
}

else
{
   pwm03 = PWM_in3;
// printf("Output is %d\n",pwm03);
}

if(i < 50)
{
   pwm01 = 127.0+100.0;
// printf("Rudder Right\n");
   i++;
}

if(i >= 50 && i <100)
{
   pwm01 = 127.0-100.0;
// printf("Rudder Left\n");
   i++;
}

if(i >= 100)
{
   i = 0;
}

} /* END Default_Routine(); */
```

Appendix C. Data from 120 ft Towing Tank Speed Tests

Throttle Setting	Time (s)	Speed (ft/s)	Distance (ft)
128	10.41	3.15081652	32.8
128	9.85	3.32994924	32.8
128	9.5	3.45263158	32.8
128	9.15	3.58469945	32.8
128	9.47	3.46356917	32.8
128	8.9	3.68539326	32.8
128	9.35	3.50802139	32.8
129	7.94	4.13098237	32.8
129	7.44	4.40860215	32.8
129	8	4.1	32.8
129	7.35	4.46258503	32.8
129	8	4.1	32.8
129	7.53	4.35590969	32.8
130	6.79	4.83063328	32.8
130	6.9	4.75362319	32.8
130	6.8	4.82352941	32.8
131	6.49	5.05392912	32.8
131	6.52	5.03067485	32.8
131	6.49	5.05392912	32.8
132	6.32	5.18987342	32.8
132	6.3	5.20634921	32.8
128	9.28	3.53448276	32.8
129	7.7	4.25974026	32.8

Appendix D. Data Processing Code from 380 ft Towing Tank Maneuverability Tests

```
% ------------------------------------------
% C Reed
% Categorize the relationship between rudder
% angle and yaw rate based on video data
% ------------------------------------------

format compact; close all;

% Test Results
% [Rudder; Throttle; Diameter; % Channel; Time];
test1 = [187;129;19.7;75.8;17.93];
test2 = [187;129;20.5;78.9;18.4];
test4 = [227;129;14.4;55.5;13.13];
test5 = [227;129;12.4;47.7;13.07];
test6 = [227;129;12.4;47.7;12.33];
test7 = [247;129;11.4;43.7;11.07];
test8 = [247;129;11.4;43.7;10.73];
test9 = [247;130;15.2;58.6;12.26];
test10 = [247;130;14.6;56.1;12.13];
test11 = [27;128;17.5;67.2;24.13];
test12 = [7;129;14.1;54.4;15.93];

% Data Manipulation
% Time Averages
time187 = (test1(5)+test2(5))/2;
time227 = (test4(5)+test5(5)+test6(5))/3;
time247 = (test7(5)+test8(5))/2;
time247f = (test9(5)+test10(5))/2;

% Angular Velocity Calculations
w187 = 2*pi/time187;
w227 = 2*pi/time227;
w247 = 2*pi/time247;
w7 = 2*pi/test12(5);
w247f = 2*pi/time247f;
w27s = 2*pi/test11(5);
w1 = -2*pi/test1(5);
w2 = -2*pi/test2(5);
w4 = -2*pi/test4(5);
w5 = -2*pi/test5(5);
w6 = -2*pi/test6(5);
w7 = -2*pi/test7(5);
w8 = -2*pi/test8(5);
w12 = 2*pi/test12(5)
wAnalyze = [w247;w227;w187];
rAnalyze = [247;227;187];
turnRr = [w8 w7 w6 w5 w4 w2 w1 0 w12 0 0 0 0 0];
rudSetr = [247 247 227 227 227 187 187 137 7 137 137 137 137 137];

% Results Figure
% figure(1); % All Results
% plot(247,w247,'p');
% hold on; grid on;
% plot(227,w227,'p');
% plot(187,w187,'p');
% plot(7,w7,'p');
% plot(247,w247f,'+');
% plot(27,w27s,'d');
%
% figure(2); % Linearity check
% plot(wAnalyze,rAnalyze,'*');
% hold on; grid on;

figure(3);
plot(turnRr,rudSetr,'*')
title('Right Turn Relationship');
xlabel('Turning Rate (rad/sec)');
```

```
ylabel('Rudder Setting');
grid on; hold on;
```

Appendix E. Data Processing Code from Inclining Tests

```
% -----------------
% Caleb Reed
% Buoyancy Testing
% 31 Jan 2006
% -----------------

% Measurements
% Transverse Distance (in)
t = [-3.0 -2-3/8 -1-7/8 -1-3/16 -5/8 -1/8 7/16 1+1/8 1+5/8 2+1/8 2+7/8];

% List (deg)
phi = [-8.35 -6.5 -4.95 -3.0 -1.15 0.35 2.01 3.97 5.5 7.15 9.50];

% Weight (lbs)
w = 1.45;

% Data Treatment
tFt = t/12;         % Transverse Distance (ft)
phiRad = phi*pi/180;% List (rad)

plot(w*tFt,tan(phiRad), '*')
grid on;
title('Reed, 31 Jan 2006, Buoyancy Tests');
xlabel('Weight*Transverse Distance (ft-lb)');
ylabel('List (tan(phi))');

slope = 0.44;   % input('What is the slope?  \n');
mInv = 1/slope;
disp = 10.04;   %lbs
GM = mInv/disp
```

FastShip 6.1.15 Hydrostatics & Stability Report

FastShip 6.1.15 Hydrostatics & Stability Report

FastShip 6.1.15 Hydrostatics & Stability Report

Appendix F. FastShip 6.1.15 Hydrostatics & Stability Report

General Model Information

February 02, 2006 10:25:37 AM — Version: FastShip 6.1.15

Project	Description
Untitled	

Partname	Mesh Density	Offset (ft)
/top/trimsrf	3 x 3	0
/top/trimsrf_1	3 x 3	0
/top/trimsrf_18	3 x 3	0
/top/trimsrf_2	3 x 3	0
/top/trimsrf_3	3 x 3	0
/top/trimsrf_4	3 x 3	0
/top/trimsrf_5	3 x 3	0

Parts Mirrored	Up Direction	Fluid Density	Refinement	Trimming
Yes	Negative	64.045 lbm/ft^3	Unrefined	Off

File Type	Path
Model	e:\reed planning boat
HTML Output	.\volume.htm

Upright Condition

Flotation Plane Definition — **Units (ft)**

Constant	N (longitudinal)	N (transverse)	N (vertical)
0.093	0.000	0.000	1.000

Overall Dimensions — **Units (ft)**

Name	Value	Min	Max
Length OA	2.829	-0.083	2.745
Length WL	2.630	-0.083	2.547
Beam OA	0.800	-0.400	0.400
Beam WL	0.745	-0.373	0.373
Depth	0.321		
Freeboard	0.135		
Draft	0.186		

Integrated Properties **Units (ft, ft^2, ft^3, lbf)**

Name	Value	Name	Value
Volume	0.157	Displacement	10.040
LCB	0.979	LCB/LWL	0.404
TCB	0.000	VCB	0.148
Max Section Area	0.080	Long'l Loc Max Area	0.892
Wetted Surface	1.994	Wetted Centroid (longitudinal)	1.049
		Wetted Centroid (transverse)	0.000
		Wetted Centroid (vertical)	0.178
		Displacement-Length Ratio	344.453

Waterplane Properties **Units (ft, ft^2, ft^3, lbf/in, ft-lbf/in)**

Name	Value	Name	Value
LCF	1.054	LCF/LWL	0.432
TCF	0.000	VCF	0.093
M Trans	-0.356	M Long	-4.742
BM Trans	0.412	BM Long	4.797
Area WP	1.647	Weight to Immerse	8.790
Moment to Trim	-1.509	Metacentric Shelf Slope	0.111
Neutral Axis Angle	0.000°	Metacentric Shelf Intercept	-0.394

Form Coefficients **Units (N/A)**

Name	Value	Name	Value
Cb	0.430	Cwp	0.840
Cx	0.578	Cp	0.744
Cp aft	0.903	Cp fwd	0.628

Station Data **Units (ft, ft^2)**

Plane Const	Wetted Girth	Immersed Area	Plane Const	Wetted Girth	Immersed Area
-0.083	0.000	0.000	-0.083	0.321	0.048
0.193	0.878	0.073	0.469	0.892	0.076
0.745	0.901	0.079	1.020	0.910	0.080

1.296	0.904	0.075	1.572	0.830	0.066
1.848	0.721	0.051	2.124	0.467	0.028
2.400	0.202	0.006	2.547	0.000	0.000

Notes

1. Dimensions are given relative to coordinate system origin, except for M Trans and M Long which are given relative to the resultant waterplane.
2. Accuracy of calculations is affected by the density of points in the surface mesh.
3. CP is based on the wetted length (not nec. = LWL). All other coefficients are based on LWL and maximum draft above.
4. The accuracy of the sectional area curve, maximum section area and location, and prismatic and midship section coefficients are affected by the surface mesh density, and the number and location of defined stations. In addition, for trimmed waterplanes the sections are no longer exactly perpendicular to the waterplane, also affecting accuracy.
5. The displacement-length ratio is defined as the computed vessel displacement in long tons divided by the cube of one-hundredth of the waterline length in feet.
6. The moment to change trim is computed with the assumption that the center of gravity is at the flotation plane.

Appendix G. Data Stream from Navigational Sensors during Autonomous Operations


```
heading,Xg,Yg,Zg,Roll,Pitch,act_lon,des_lon,act_lat,des_lat,speed,act_course,des_course,dist,rud_set,
176.3,-6.253,14.15,92.71,446.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-1.365,11.71,91.49,446.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,1.078,14.15,92.71,447.0,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,1.078,15.38,96.37,447.1,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.031,11.71,90.26,447.2,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-8.696,14.15,91.49,447.2,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.198,15.99,91.49,447.2,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-4.420,14.15,92.71,447.3,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.253,12.32,92.71,447.4,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.864,10.49,93.93,447.5,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-2.587,14.15,90.26,447.5,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.1437,9.271,91.49,447.5,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.809,10.49,90.26,447.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,1.078,13.54,95.76,447.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.1437,14.15,93.93,447.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.7546,9.271,95.15,447.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.864,14.15,90.26,447.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.031,10.49,92.71,447.8,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.198,8.882,90.26,447.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.1437,10.49,90.26,447.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-7.475,15.38,89.65,448.0,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.7546,15.38,91.49,448.1,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-1.976,11.71,96.37,448.1,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.642,9.271,92.71,448.1,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.1437,11.71,92.71,448.2,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.031,13.54,92.71,448.2,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-1.365,14.15,93.93,448.3,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-2.587,15.38,91.49,448.4,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.809,12.93,93.32,448.5,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-1.365,14.76,93.93,448.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.253,12.93,89.65,448.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.198,9.882,93.93,448.8,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.809,12.93,92.71,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,1.078,9.271,92.71,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-3.809,11.71,92.71,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-0.1437,13.54,91.49,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-4.420,14.76,92.71,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.642,8.049,90.26,448.9,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.4,-5.642,10.49,90.26,449.0,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.5,-6.253,17.82,98.82,449.7,305.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.7,-8.696,21.49,97.60,450.6,305.4,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.7,-2.587,27.59,100.6,450.9,305.1,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.5,-3.809,27.59,99.43,450.7,304.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.4,-4.420,30.04,101.2,450.9,304.4,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.253,20.87,89.04,450.9,303.9,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-3.809,19.04,82.93,450.3,303.5,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-5.642,19.65,78.04,451.1,302.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,-4.420,15.38,73.16,451.9,301.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-6.253,9.882,73.16,452.4,300.4,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,1.078,10.49,82.93,452.9,298.9,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-1.976,19.65,95.76,453.3,297.5,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-5.031,12.32,93.93,453.6,296.5,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.4,0.4672,16.60,87.82,454.4,295.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.5,3.521,21.49,95.15,455.0,295.2,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.5,-2.587,20.87,80.49,455.6,294.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.6,-6.864,23.93,71.94,456.0,294.3,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.5,-8.696,14.15,87.82,455.8,293.4,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.4,-13.58,14.76,92.71,455.8,292.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.3,-13.58,15.99,92.71,455.5,292.1,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,-3.809,11.71,90.87,455.3,291.7,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,-5.642,12.93,89.65,454.8,291.1,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-6.253,6.827,92.71,455.1,290.2,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,-2.587,6.827,92.71,455.8,289.8,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-0.1437,14.76,97.60,455.9,289.6,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,2.911,14.15,92.10,455.8,289.3,76.485314,76.482758,38.986075,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,-2.587,10.49,91.49,455.8,289.3,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
175.8,-3.809,11.71,87.82,455.6,289.4,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
175.8,-1.976,10.49,81.10,455.6,289.4,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.0,-3.809,11.71,80.49,456.7,289.5,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.2,-11.14,17.82,90.26,458.5,289.2,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.4,-2.587,20.26,87.82,459.4,289.2,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.3,-5.031,15.38,87.82,459.3,289.2,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.2,-9.307,15.38,90.26,459.3,289.2,76.485314,76.482758,38.986065,38.986552,1.0,222.7,80.909,725.300,249.5,
176.2,-13.58,24.54,97.60,459.7,288.9,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
176.2,-11.14,21.49,91.49,460.0,288.9,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
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176.0,-0.1437,16.60,85.38,459.3,288.1,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.8,-1.976,11.71,103.7,458.5,286.8,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.6,-12.36,15.38,105.5,457.6,285.6,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.5,-1.976,27.59,97.60,457.4,284.8,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.7,-11.14,27.59,74.38,458.2,285.1,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.7,-2.587,12.32,80.49,458.6,285.9,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.7,-1.365,10.49,97.60,458.3,287.3,76.485314,76.482758,38.986065,38.986552,1.0,230.9,80.909,725.300,249.5,
175.7,3.521,8.660,85.99,457.7,288.7,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.8,8.409,12.32,109.8,457.7,289.4,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.8,2.911,11.71,96.37,457.4,290.0,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.8,-14.80,4.383,105.5,457.4,291.0,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.8,-3.809,9.882,98.82,456.7,290.8,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.9,3.521,26.37,91.49,457.9,291.1,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
175.9,-6.864,20.26,103.7,457.5,290.9,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
176.0,-0.1437,10.49,81.71,458.5,290.3,76.485314,76.482758,38.986065,38.986552,0.57,246.2,80.909,725.300,249.5,
176.2,-0.1437,20.26,96.98,459.7,290.2,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.3,5.965,18.43,86.60,460.0,290.0,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.4,-14.80,19.04,85.99,460.9,290.2,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.4,7.187,20.26,94.54,460.5,290.2,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.3,8.409,14.15,87.82,460.0,290.2,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.4,-13.58,19.04,81.71,460.5,290.5,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.3,-1.976,16.60,82.93,460.3,290.6,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.1,-3.198,26.37,100.0,459.1,290.8,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
176.0,9.020,9.271,85.99,458.7,290.5,76.485314,76.482758,38.986065,38.986552,0.34,215.1,80.909,725.300,249.5,
175.9,-3.809,12.93,93.32,458.4,290.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-1.365,24.54,93.32,458.0,289.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,2.300,23.93,90.26,458.7,289.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-3.809,10.49,80.49,459.8,289.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-3.809,10.49,78.66,460.2,290.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,5.354,2.550,87.82,460.7,291.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,-6.864,20.26,96.37,460.7,292.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-0.1437,19.65,91.49,460.1,292.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,-1.976,18.43,107.3,459.8,293.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,2.300,24.54,101.2,459.3,293.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-0.1437,23.32,100.0,458.9,293.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,11.10,90.26,459.0,293.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-5.031,14.76,93.93,459.1,294.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,-3.809,12.93,91.49,459.4,294.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-0.1437,5.605,90.26,458.9,294.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-5.642,14.15,95.15,457.8,295.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-1.976,11.71,105.5,457.9,295.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-2.587,15.99,97.60,458.4,296.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,2.300,14.15,92.71,458.6,296.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,12.93,96.98,458.6,296.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,19.04,87.82,459.1,296.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,-2.587,19.04,99.43,459.6,296.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,-0.1437,15.99,92.71,459.7,297.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,5.965,26.37,92.71,460.0,297.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,-6.864,16.60,86.60,460.2,297.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,1.078,19.04,92.71,459.6,297.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
3.307,9.631,16.60,95.76,459.0,297.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,6.576,11.71,90.26,458.4,297.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.078,11.71,87.82,458.1,298.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,2.911,10.49,93.93,458.1,299.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,1.078,12.93,95.15,459.4,299.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.1,-2.587,15.38,87.82,461.1,300.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.2,0.4672,19.04,85.38,461.5,300.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
176.0,-3.809,20.26,87.82,460.1,300.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,15.38,90.26,457.7,300.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,2.300,9.271,101.2,456.5,300.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,1.078,12.32,102.4,456.7,300.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-2.587,11.71,98.82,458.4,300.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,1.078,12.93,95.15,460.1,301.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,3.521,11.71,89.04,460.6,301.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-0.1437,16.60,94.54,459.7,302.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,0.4672,10.49,92.71,458.3,302.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-1.976,7.438,90.26,457.7,302.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,8.049,90.26,458.1,303.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,5.965,11.10,89.04,459.0,303.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,2.300,11.71,92.71,459.5,303.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,2.911,11.71,92.71,459.7,303.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,10.85,12.93,96.37,459.3,303.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.132,11.10,90.26,458.7,303.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,9.271,92.71,458.1,303.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-3.198,6.827,90.26,458.0,303.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,10.49,96.37,458.8,303.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,11.71,90.26,459.9,303.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,1.078,11.10,87.82,460.9,303.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,2.300,9.271,87.21,460.7,304.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
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175.7,2.911,17.21,92.71,459.8,304.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,8.409,14.15,98.82,458.6,304.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-1.365,3.161,93.93,458.3,304.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,5.965,11.71,92.71,459.2,305.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,11.71,95.76,460.4,305.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,14.76,93.93,461.0,305.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,1.689,14.15,92.71,461.0,305.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,1.078,12.93,87.82,460.5,305.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,2.300,11.71,89.04,460.1,306.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,9.020,14.15,97.60,459.7,306.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,11.71,95.76,459.6,306.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,5.965,10.49,95.76,459.8,306.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,0.4672,10.49,89.04,460.1,306.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,8.409,12.32,87.82,460.1,306.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,7.187,14.15,91.49,459.8,306.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,11.71,97.60,459.7,306.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.078,9.271,97.60,460.0,306.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,7.187,12.93,97.60,460.9,307.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,13.54,90.26,461.6,307.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,11.71,85.38,461.6,307.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,2.300,11.71,92.71,461.0,307.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-0.7546,14.15,90.26,460.5,307.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.911,9.882,97.60,460.5,307.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,10.49,92.71,460.9,308.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.078,6.827,89.04,461.4,308.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,14.15,92.10,461.4,308.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,9.271,93.93,460.9,308.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.078,8.660,92.71,460.3,307.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,9.271,95.76,460.2,307.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,8.409,6.827,96.98,460.9,307.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,1.078,15.99,95.76,462.0,308.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,2.300,8.049,90.26,462.8,308.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.9,1.078,9.271,85.99,462.9,309.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,4.743,13.54,87.82,462.2,309.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.911,9.882,93.93,461.3,309.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.300,11.71,97.60,460.7,308.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-1.365,11.71,97.60,460.8,308.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,14.15,94.54,461.4,308.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,10.24,14.76,92.71,461.9,309.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-2.587,10.49,90.26,461.9,309.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,10.49,91.49,461.6,310.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,7.187,8.660,93.93,461.1,310.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,11.71,97.60,461.1,310.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,6.827,100.0,461.8,310.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-0.1437,10.49,93.93,462.8,311.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-0.1437,14.15,87.21,463.3,311.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,2.300,18.43,88.43,463.0,310.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,11.10,93.93,462.2,310.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.300,11.10,97.60,461.8,309.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.743,11.71,96.98,462.0,310.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,14.15,89.65,462.9,310.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,1.689,14.15,91.49,463.6,311.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,12.93,90.26,463.6,312.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,5.354,14.15,92.71,463.0,312.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.911,9.271,95.76,462.3,312.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,14.15,92.71,462.0,313.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.689,9.271,95.15,462.2,313.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,6.827,94.54,462.3,313.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,9.271,93.93,462.3,313.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-0.1437,6.827,92.71,462.1,313.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.911,9.271,95.76,462.1,313.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-2.587,11.71,95.76,462.4,313.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,11.71,95.15,463.1,313.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,7.798,17.82,96.37,463.5,314.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.132,11.71,92.71,463.3,314.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,13.54,96.37,462.8,314.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,4.132,9.882,95.76,462.6,315.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.300,12.93,97.60,462.8,315.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.743,12.32,96.37,463.5,314.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.078,14.15,93.93,464.1,314.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,4.743,10.49,92.71,464.1,315.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,4.743,14.15,91.49,463.8,316.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-1.365,12.32,89.04,463.3,316.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.689,12.32,90.26,463.0,316.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,8.660,93.93,463.1,316.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,5.965,11.71,95.15,463.4,316.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.911,10.49,90.26,463.5,316.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,15.99,95.76,463.0,317.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,2.911,10.49,95.76,462.5,317.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,

175.4,2.300,14.15,100.0,462.2,316.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,5.965,13.54,97.60,462.8,316.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.132,11.10,95.76,463.9,316.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,5.965,9.271,90.26,465.0,317.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,14.76,92.71,465.5,318.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-2.587,11.71,92.71,465.3,318.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,5.354,11.71,96.37,464.5,317.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.078,13.54,92.71,463.6,317.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,1.078,9.882,93.93,463.0,318.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,11.71,92.71,463.0,319.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.911,17.82,91.49,463.7,319.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,13.54,90.26,464.2,319.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,4.743,12.32,93.93,464.2,319.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,3.521,9.271,93.93,463.3,320.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,8.409,11.71,92.71,463.1,320.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,1.689,6.827,96.37,463.7,320.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,0.4672,14.15,94.54,464.7,320.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,15.38,92.71,465.7,321.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-0.1437,11.71,90.87,466.2,321.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,1.078,15.38,96.37,465.9,321.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.078,6.827,88.43,465.4,321.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,13.54,96.37,464.8,321.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,8.049,96.37,464.8,321.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,11.71,94.54,465.0,321.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-1.365,13.54,92.71,465.2,322.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,10.49,90.87,465.1,322.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,11.71,93.93,464.6,321.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,3.521,12.32,96.37,464.4,321.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,7.798,14.15,98.21,464.7,321.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-0.1437,16.60,90.26,465.5,321.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,13.54,95.15,466.2,322.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.078,17.21,92.71,466.3,322.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,12.93,93.93,465.8,322.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-0.7546,6.827,96.98,465.2,322.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-0.7546,11.71,94.54,465.1,322.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,0.4672,9.882,92.71,465.3,323.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,4.132,11.71,87.82,465.4,323.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.689,14.15,92.71,465.5,323.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.911,11.10,95.76,465.5,324.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,7.438,92.71,465.6,324.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.689,11.71,92.10,466.0,324.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-2.587,9.271,91.49,466.5,324.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,-0.1437,10.49,89.04,466.6,324.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,10.49,91.49,466.3,325.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.300,8.660,96.37,465.8,325.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,0.4672,12.32,92.71,465.7,325.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,12.93,96.37,465.9,325.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,14.15,93.93,466.1,325.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,-1.365,14.15,91.49,468.0,326.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,3.521,14.15,89.04,467.6,327.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,13.54,93.93,466.6,327.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,11.71,89.04,467.0,327.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,-0.7546,10.49,92.71,466.3,327.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,1.689,12.93,95.15,466.3,328.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,5.965,12.32,97.60,467.1,328.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,1.689,9.271,92.71,468.1,329.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.8,3.521,12.32,92.71,468.5,329.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.7,5.965,16.60,96.98,468.0,328.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,1.689,11.71,92.71,467.0,328.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,6.576,5.605,95.76,466.2,328.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.3,1.689,10.49,97.60,466.1,329.4,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,-1.365,9.882,96.37,466.7,329.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,9.882,90.87,467.5,329.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,7.187,9.882,90.26,468.0,329.8,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,17.21,91.49,468.0,329.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,2.300,17.82,89.04,467.7,330.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.4,3.521,10.49,97.60,467.4,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,-0.1437,11.71,94.54,467.4,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,11.71,97.60,467.8,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.743,14.15,94.54,468.2,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,14.15,93.93,468.3,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,4.743,14.15,95.76,468.2,330.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,3.521,12.93,92.71,468.2,330.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,1.078,7.438,92.71,468.3,330.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,2.300,15.38,92.71,468.5,331.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-1.365,12.93,91.49,468.5,331.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.6,-0.1437,12.93,96.37,468.3,331.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,3.521,11.71,90.26,468.0,331.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
175.5,5.965,12.32,95.76,468.2,332.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,

175.5,5.965,11.71,96.37,468.4,331.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
133.7,34.06,5.605,104.9,469.6,332.3,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
121.3,91.49,25.15,141.5,471.7,331.2,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
91.16,-5.642,60.59,117.1,473.7,331.0,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
104.6,20.01,-93.36,46.28,472.9,331.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
125.3,13.29,20.87,104.9,471.2,331.6,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
74.85,22.46,-16.99,37.72,469.3,330.7,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
41.72,5.965,6.827,92.71,468.2,330.9,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
19.26,-6.253,11.10,96.37,468.2,331.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
198.2,-0.1437,20.87,104.3,469.1,331.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
335.8,-1.365,15.38,98.82,470.3,331.5,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
335.8,1.078,14.15,90.26,470.5,332.1,76.485333,76.482758,38.986065,38.986552,0.0,000.0,80.909,725.300,7.557,
335.9,2.300,12.32,93.93,469.6,333.3,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
336.0,3.521,14.15,97.60,469.1,333.6,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
336.0,5.965,10.49,100.0,468.9,333.4,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
61.83,23.68,21.49,95.15,468.9,333.6,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
97.42,7.798,75.25,103.7,469.2,333.6,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
47.49,8.409,29.43,21.84,469.7,333.3,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
103.7,38.95,41.04,73.16,470.6,332.5,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
75.98,-22.13,-95.81,53.61,471.3,332.3,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
116.7,66.44,132.6,102.4,471.3,331.9,76.485362,76.482758,38.986065,38.986552,1.9,267.3,81.253,725.300,7.557,
85.05,-3.198,-146.5,110.4,470.3,331.7,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
91.92,43.23,66.70,60.94,469.7,331.4,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
109.6,-52.68,36.15,76.82,469.8,331.1,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
110.5,42.01,-19.44,106.1,470.3,331.1,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
109.7,-8.696,-48.76,53.61,471.0,331.4,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
101.9,13.90,162.0,109.8,471.8,331.4,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
88.77,-22.13,-55.48,76.82,472.5,331.0,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
90.12,-25.19,-6.613,92.71,472.8,330.8,76.485362,76.482758,38.986065,38.986552,2.0,272.6,81.253,753.163,7.557,
78.83,-7.475,50.81,117.1,472.3,330.1,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
114.9,69.50,173.0,87.82,471.6,329.3,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
113.6,2.300,-31.66,80.49,471.0,329.3,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
107.3,42.62,-105.5,37.72,471.0,329.4,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
77.43,20.62,-149.5,71.94,471.4,329.9,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
67.38,13.29,120.4,53.00,472.1,330.2,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
116.4,13.29,-79.31,119.5,472.9,330.0,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
111.1,18.18,-105.5,55.44,473.0,329.7,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
74.34,7.798,-63.43,124.4,472.5,329.1,76.485371,76.482758,38.986065,38.986552,2.7,284.2,81.253,753.163,7.557,
65.28,22.46,31.26,93.93,471.7,328.9,76.485390,76.482758,38.986075,38.986552,3.4,292.8,81.253,753.163,7.557,
113.5,-3.809,9.271,144.0,472.3,329.3,76.485390,76.482758,38.986075,38.986552,3.4,292.8,81.253,753.163,7.557,
97.15,5.965,87.47,76.82,472.7,329.0,76.485390,76.482758,38.986075,38.986552,3.4,292.8,81.253,753.163,7.557,
105.9,71.94,-2.947,58.49,472.8,328.8,76.485390,76.482758,38.986075,38.986552,3.4,292.8,81.253,753.163,7.557,
84.02,-28.24,31.26,133.6,472.8,328.6,76.485390,76.482758,38.986075,38.986552,3.4,292.8,81.253,753.163,7.557,
116.3,25.51,163.8,108.5,472.5,328.6,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
103.3,24.29,82.58,109.8,472.3,328.6,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
114.6,10.85,36.15,108.5,472.3,328.9,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
98.50,30.40,-190.5,71.32,472.1,329.0,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
63.31,-16.02,5.605,122.0,471.8,329.0,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
90.65,18.79,0.7178,100.0,472.0,328.8,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
95.66,16.96,-82.98,85.38,472.5,328.5,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
98.29,-11.14,-42.04,102.4,473.2,328.3,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
113.6,20.62,61.20,107.3,473.7,328.4,76.485409,76.482758,38.986079,38.986552,3.2,304.9,81.253,753.163,7.557,
99.62,25.51,14.76,95.76,473.7,328.1,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
112.3,43.84,160.1,84.15,473.4,327.9,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
91.47,31.01,-151.4,78.04,472.8,327.5,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
68.08,63.39,168.1,69.49,472.7,327.5,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
102.2,18.79,168.7,85.99,473.0,327.6,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
67.41,53.00,-65.26,65.83,473.3,328.0,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
98.70,-2.587,0.1069,93.32,473.4,328.3,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
107.7,-25.80,-46.93,117.1,473.4,328.3,76.485419,76.482758,38.986088,38.986552,3.2,317.8,81.253,753.163,7.557,
64.46,46.28,167.5,70.71,473.4,328.7,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
73.50,9.020,-134.3,53.61,473.2,328.2,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
84.00,-28.24,65.47,92.71,473.3,327.8,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
104.3,3.521,80.14,91.49,473.4,327.8,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
79.02,68.28,38.59,82.93,473.4,327.8,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
74.48,42.62,102.1,92.71,473.1,328.3,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
110.5,51.78,12.93,71.94,472.3,329.0,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
64.68,-2.587,-24.94,162.3,472.4,329.2,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
85.21,-13.58,-120.2,133.0,473.3,329.3,76.485419,76.482758,38.986094,38.986552,3.2,328.1,81.253,753.163,7.557,
111.5,21.85,34.93,97.60,474.1,329.9,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
65.69,-28.85,-73.81,95.76,474.1,330.7,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
79.34,-28.24,38.59,93.93,473.4,330.7,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
106.7,62.17,173.0,87.82,473.2,330.1,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
98.79,64.61,129.0,100.0,473.7,329.9,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
93.20,-17.86,-68.93,126.3,474.7,330.1,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
108.4,27.95,-53.04,79.88,475.5,330.1,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
68.13,-1.976,12.32,67.05,475.3,330.2,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
99.38,48.73,53.25,54.83,474.7,330.5,76.485438,76.482758,38.986104,38.986552,3.2,339.9,81.253,753.163,7.557,
87.53,37.73,5.605,95.15,474.2,330.9,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,

88.32,34.06,-54.26,106.1,474.2,331.1,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
79.82,31.01,0.7178,79.27,474.6,331.1,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
73.03,34.06,-23.72,108.5,475.0,331.4,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
93.26,13.90,94.80,85.38,475.2,331.6,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
84.20,13.29,68.53,102.4,474.9,331.8,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
73.01,23.07,108.2,117.1,474.6,331.3,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
101.4,-18.47,51.42,126.9,474.5,331.5,76.485438,76.482758,38.986117,38.986552,3.3,343.1,81.253,753.163,7.557,
111.1,49.34,89.91,70.10,474.2,332.0,76.485438,76.482758,38.986132,38.986552,3.2,346.7,81.253,753.163,7.557,
86.86,29.18,-55.48,34.06,474.5,331.7,76.485438,76.482758,38.986132,38.986552,3.2,346.7,81.253,753.163,7.557,
109.8,-10.52,41.04,46.28,475.2,331.7,76.485438,76.482758,38.986132,38.986552,3.2,346.7,81.253,753.163,7.557,
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107.9,-11.14,28.82,168.4,694.0,835.5,76.485142,76.485314,38.987095,38.986918,3.1,227.3,225.00,46.1987,140.5,
130.1,-3.809,12.93,85.38,693.0,836.0,76.485161,76.485314,38.987086,38.986918,3.3,223.8,225.00,46.1987,135.0,
86.32,-8.086,66.70,136.7,693.1,836.4,76.485161,76.485314,38.987086,38.986918,3.3,223.8,225.00,46.1987,135.0,
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109.7,51.78,5.605,24.28,695.2,838.1,76.485190,76.485314,38.987067,38.986918,3.6,239.6,225.00,46.1987,157.7,
89.31,-16.63,-68.93,45.66,695.8,837.8,76.485190,76.485314,38.987067,38.986918,3.6,239.6,225.00,46.1987,157.7,
119.9,30.40,43.48,104.9,696.1,849.0,76.485257,76.485314,38.987048,38.986918,3.1,244.7,180.00,36.4223,245.5,
127.0,19.40,-2.947,41.39,703.4,852.4,76.485266,76.485314,38.987042,38.986918,2.8,224.9,180.00,36.4223,200.5,
125.65,-33.13,-6.002,109.8,706.8,852.0,76.485285,76.485314,38.987019,38.986918,3.1,186.6,270.00,36.4223,7.557,
109.2,-9.307,138.7,113.4,703.3,847.8,76.485285,76.485314,38.987010,38.986752,2.9,185.7,180.00,0.00000,145.6,
124.7,1.078,-34.71,36.50,702.8,858.9,76.485295,76.485314,38.986971,38.986752,3.1,227.8,180.00,72.8447,205.9,
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90.67,23.07,17.21,128.1,713.3,870.7,76.485333,76.485705,38.986828,38.986666,2.9,187.3,251.56,92.7157,7.557,
134.7,13.29,56.92,92.10,713.8,869.4,76.485333,76.485705,38.986828,38.986666,2.9,187.3,251.56,92.7157,7.557,
68.80,-40.46,-18.22,175.8,711.1,856.5,76.485342,76.485705,38.986819,38.986666,2.6,211.1,251.56,92.7157,28.53,
68.25,-0.7546,-47.54,109.8,710.9,855.3,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
72.09,4.132,-51.82,100.0,710.9,854.5,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
69.12,57.89,71.58,60.94,710.0,854.3,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
98.88,21.85,36.76,26.11,708.7,854.4,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
69.74,-9.918,55.70,109.8,707.7,854.4,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
70.12,21.85,-37.77,122.0,707.2,854.6,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
75.24,27.95,-12.72,74.99,707.8,854.8,76.485342,76.485705,38.986813,38.986666,2.4,262.1,251.56,92.7157,152.3,
90.64,7.187,11.71,101.2,709.7,856.5,76.485362,76.485705,38.986819,38.986666,2.6,309.9,251.56,92.7157,228.6,
108.0,20.62,42.26,80.49,708.0,856.5,76.485362,76.485705,38.986819,38.986666,2.6,309.9,251.56,92.7157,228.6,
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98.86,20.62,13.54,113.4,707.9,861.2,76.485371,76.485705,38.986828,38.986666,3.3,324.8,251.56,92.7157,249.5,
82.93,1.078,6.827,56.05,710.3,864.7,76.485371,76.485705,38.986828,38.986666,3.3,324.8,251.56,92.7157,249.5,
91.98,34.06,-71.37,125.0,710.3,865.7,76.485371,76.485705,38.986838,38.986666,3.3,312.0,251.56,92.7157,233.9,
89.62,-1.365,-4.169,24.28,710.4,866.3,76.485371,76.485705,38.986838,38.986666,3.3,312.0,251.56,92.7157,233.9,
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120.2,30.40,-15.77,125.7,713.4,874.8,76.485409,76.485705,38.986842,38.986666,2.9,269.6,243.43,92.7157,172.6,
93.40,15.74,-30.44,87.82,713.4,875.6,76.485409,76.485705,38.986842,38.986666,2.9,269.6,243.43,92.7157,172.6,
95.93,22.46,-12.72,68.27,718.3,877.9,76.485447,76.485705,38.986828,38.986666,2.9,232.5,243.43,67.5095,117.2,
109.5,26.12,-23.72,65.83,718.5,876.5,76.485447,76.485705,38.986828,38.986666,2.9,232.5,243.43,67.5095,117.2,
103.0,24.29,0.1069,80.49,719.2,876.6,76.485447,76.485705,38.986828,38.986666,2.9,232.5,243.43,67.5095,117.2,
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99.34,2.300,-13.94,53.61,718.5,875.8,76.485486,76.485705,38.986819,38.986666,2.9,243.1,243.43,67.5095,136.4,
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120.6,5.965,-29.82,143.4,719.8,893.1,76.485524,76.485705,38.986819,38.986666,3.3,263.1,225.00,46.1987,189.3,
120.0,-28.24,114.3,107.3,719.5,893.5,76.485524,76.485705,38.986819,38.986666,3.3,263.1,225.00,46.1987,189.3,
116.8,-20.91,26.98,65.83,719.8,894.4,76.485543,76.485705,38.986813,38.986666,3.1,243.5,225.00,46.1987,162.7,
120.7,-1.365,-22.49,102.4,721.3,897.8,76.485562,76.485705,38.986804,38.986666,2.8,220.8,225.00,46.1987,129.9,
123.3,1.078,-39.60,131.2,722.1,898.9,76.485571,76.485705,38.986800,38.986666,3.1,206.9,225.00,46.1987,101.2,
117.1,-3.809,-14.55,114.7,723.1,898.5,76.485571,76.485705,38.986800,38.986666,3.1,206.9,225.00,46.1987,101.2,

129.6,-28.24,97.24,100.6,724.4,895.4,76.485571,76.485705,38.986781,38.986666,3.2,208.1,225.00,46.1987,104.1,
93.28,-0.7546,-66.48,100.0,724.8,894.8,76.485571,76.485705,38.986781,38.986666,3.2,208.1,225.00,46.1987,104.1,
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72.32,10.85,-25.55,115.9,721.5,887.5,76.485619,76.486477,38.986765,38.986418,2.7,278.5,249.44,0.00000,176.4,
99.46,36.51,88.69,46.89,720.4,887.7,76.485616.486477,38.986765,38.986418,3.1,299.8,249.44,252.258,210.8,
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119.5,32.84,111.9,90.87,721.7,894.9,76.485638,76.486477,38.986765,38.986418,3.1,299.8,249.44,252.258,210.8,
93.66,16.96,-19.44,101.2,722.7,897.4,76.485648,76.486477,38.986775,38.986418,3.3,298.1,249.44,252.258,207.5,
97.85,-9.307,-39.60,128.1,722.7,896.8,76.485648,76.486477,38.986775,38.986418,3.3,298.1,249.44,252.258,207.5,
130.6,38.95,57.53,64.60,725.2,904.6,76.485676,76.486477,38.986781,38.986418,3.1,256.9,246.80,252.258,151.7,
121.1,9.020,32.48,82.93,728.0,904.3,76.485743,76.486477,38.986765,38.986418,2.9,247.9,246.80,226.976,138.7,
112.3,42.62,58.14,45.05,727.4,904.5,76.485743,76.486477,38.986765,38.986418,2.9,247.9,246.80,226.976,138.7,
89.86,-16.02,116.7,139.1,727.6,905.9,76.485753,76.486477,38.986762,38.986418,2.9,259.6,246.80,226.976,155.3,
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122.1,-1.365,3.161,166.0,729.6,910.8,76.485772,76.486477,38.986762,38.986418,2.9,265.4,246.80,226.976,162.8,
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95.29,-6.253,-18.22,137.9,730.7,918.1,76.485800,76.486477,38.986742,38.986418,2.9,250.7,243.43,202.528,147.8,
99.59,-8.696,89.91,125.0,731.3,917.9,76.485800,76.486477,38.986742,38.986418,2.9,250.7,243.43,202.528,147.8,
132.0,18.79,9.271,85.99,731.2,918.2,76.485800,76.486477,38.986742,38.986418,2.9,250.7,243.43,202.528,147.8,
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128.4,12.68,12.32,106.1,731.6,919.2,76.485819,76.486477,38.986742,38.986418,2.9,246.3,243.43,202.528,141.4,
131.8,-6.253,67.92,107.3,731.6,919.4,76.485819,76.486477,38.986742,38.986418,2.9,246.3,243.43,202.528,141.4,
134.4,23.68,50.81,100.0,732.0,920.1,76.485819,76.486477,38.986742,38.986418,2.9,246.3,243.43,202.528,141.4,
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107.9,-12.97,49.59,125.7,733.4,920.4,76.485819,76.486477,38.986742,38.986418,2.9,246.3,243.43,202.528,141.4,
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98.26,-16.02,103.3,107.3,732.2,921.1,76.485829,76.486477,38.986737,38.986418,2.8,242.7,243.43,202.528,135.8,
112.1,-10.52,-59.76,131.8,733.3,920.7,76.485829,76.486477,38.986737,38.986418,2.8,242.7,243.43,202.528,135.8,
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122.9,20.01,44.09,62.16,734.2,921.3,76.485848,76.486477,38.986737,38.986418,2.9,245.9,243.43,202.528,140.8,
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117.5,30.40,16.60,58.49,733.3,922.3,76.485848,76.486477,38.986737,38.986418,2.9,245.9,243.43,202.528,140.8,
97.73,-8.696,94.80,111.6,733.4,922.5,76.485848,76.486477,38.986737,38.986418,2.9,245.9,243.43,202.528,140.8,
124.1,34.06,14.15,75.60,733.3,925.4,76.485877,76.486477,38.986727,38.986418,2.9,255.9,239.03,202.528,160.6,
121.8,3.521,41.65,109.8,733.8,926.2,76.485896,76.486477,38.986723,38.986418,3.1,259.3,239.03,179.256,165.0,
93.38,-17.25,-11.50,118.3,734.1,925.9,76.485896,76.486477,38.986723,38.986418,3.1,259.3,239.03,179.256,165.0,
111.4,16.96,-38.38,107.3,734.1,926.3,76.485896,76.486477,38.986723,38.986418,358.4,239.03,179.256,163.8,
127.2,7.187,102.1,70.71,735.6,928.3,76.485905,76.486477,38.986723,38.986418,2.9,258.4,239.03,179.256,163.8,
113.7,14.513,37.73,67.31,735.7,928.7,76.485905,76.486477,38.986723,38.986418,2.9,258.4,239.03,179.256,163.8,
118.3,5.965,6.827,41.39,735.7,929.4,76.485905,76.486477,38.986723,38.986418,3.1,253.2,239.03,179.256,157.1,
89.79,24.29,-32.88,68.27,736.2,932.8,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
118.5,10.85,-50.60,91.49,736.5,933.2,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
82.25,31.62,-17.61,48.72,736.8,933.0,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
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120.4,11.46,0.1069,106.7,737.9,933.3,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
102.7,-14.19,52.64,92.71,738.4,933.3,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
97.36,23.07,30.04,51.16,738.6,933.7,76.485924,76.486477,38.986714,38.986418,2.8,249.6,248.19,179.256,139.2,
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